Contractor's Report to the Board

Draft Final Report:

Evaluation of Conversion Technology Processes and Products

September 2004

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Disclaimer

The statements and conclusions in this report are those of the authors and not necessarily those of the California Integrated Waste Management Board. The report contains some information obtained from companies that could not be directly verified through third-party sources. The mention of commercial products, their source, or their use in connection with the material reported herein is not to be construed as actual or implied endorsement of such products.

Executive Summary

The diversion of materials from landfill is one of the central goals of the California Integrated Waste Management Board (CIWMB) as well as an important societal issue. Diversion efforts have increased substantially in California since the passage of the Integrated Waste Management Act in 1989, which established a target of 50 percent diversion from landfills by 2000. Although the diversion rate in California is estimated to be approximately 47 percent, more than 39 million tons of material is still disposed of in landfills.

Of the materials landfilled, 79 percent is organic (biomass and plastic carbonaceous material) and could potentially be processed to provide chemical energy or be converted into other useful products. For example, the 31 million tons of organic waste currently landfilled annually contains the equivalent energy of more than 60 million barrels of crude oil, or could support 2500 MW of electrical power or 22.1 TWh of electric energy (if all energetic components were to be converted to electricity by conventional means), representing about 10 percent of the in-state electrical generation and about 8 percent of the State's electric energy consumption (276.6 TWh/year).

Potential options for reducing the current amount of waste disposed in landfills include reducing the generation of waste, increasing the amount recycled, and/or diverting a portion of the stream through other conversion processes. The recycling market plays an important role in the waste infrastructure. Much of the readily recyclable material is already pulled from the waste stream due to market and local jurisdiction efforts to satisfy diversion required by the Integrated Waste Management Act. Programs to reduce waste at the source (i.e., producer responsibility laws) are also used elsewhere, such as Europe.

Although these programs have had some success, it is unlikely that these source reduction programs will be widely adopted in the United States without greater public and political support. The combustion or incineration of waste is another option that has increasingly been used in Europe and Japan where strict environmental regulations are in force. Incineration remains controversial, however, due to public perceptions of environmental impacts and other issues even though combustion systems have been significantly improved in recent years. Barriers to waste incineration will probably not be overcome in California in the foreseeable future.

To further explore options for reducing the landfill disposal of organics, legislators and the CIWMB have put in place several new programs. Assembly Bill 2770 (Matthews, Chapter 740, Statutes of 2002) initiates information-gathering activities, including this report, which evaluates technology options, life-cycle analyses, and market assessments.[*]

A main focus of these programs includes the evaluation of conversion technologies, or methods that do not employ full oxidative combustion (commonly called incineration). These include thermochemical processes such as pyrolysis and gasification and biochemical processes such as aerobic and anaerobic digestion and fermentation. Questions pertaining to these technologies include the types of feedstocks that can potentially be utilized, the technical viability of the processes, the products from the processes, their environmental impacts, and financial, economic, social, and political feasibility.

This report provides a technical evaluation of conversion technologies, addressing issues related to technical viability and environmental impacts. As part of this evaluation, a survey of companies, institutions, and technology developers was conducted in combination with an evaluation of information available in the open literature. An extensive database of companies, institutions, and technology

[*] AB 2770 also includes a definition for gasification that is technically inaccurate.

developers were surveyed by questionnaire. This database was developed through separate work funded by CIWMB (available at http://cbc1.engr.ucdavis.edu/conv/home.htm).

The survey questions addressed issues such as commercial status, typical feedstocks, applicability to municipal solid waste (MSW), and information about the performance of the technology such as energy conversion efficiency and mass reduction efficiency. Of the nearly 400 companies, institutions, and technology developers that we initially contacted or attempted to contact, a total of 69 responded. This included information on 18 pyrolysis technologies, 22 gasification technologies, 11 biochemical processes, 10 plasma arc technologies, and 9 technologies related to catalytic cracking, feedstock preparation, or other issues.

Of these responses, approximately 70 percent provided answers to the survey questions in varying level of detail, with remaining responders providing supplementary materials. The focus of this report is an overall technical evaluation, but certain social, economic, and regulatory issues are addressed as appropriate. Although information was obtained from organizations with a commercial interest in conversion technologies, a formal vendor evaluation was not conducted.

Based on the information gathered, the relative merits of the various conversion technologies were evaluated with emphasis on the following criteria: (a) reduction in total MSW mass flow to landfills, (b) environmental impact and (c) creation of revenue from the marketing of useful energy products. This program is part of the larger effort that includes a life cycle analysis (LCA) by RTI International and a market analysis by Hilton Farnkopf & Hobson, LLC.

Conversion Pathway Definitions

An important aspect of this report is to provide consistent and accurate conversion process definitions that can be utilized in legislative or other areas. Although AB 2770 includes a definition for gasification, from a scientific standpoint this definition is overly restrictive and does not encompass the full range of technologies available. Under this definition, processes that gasify waste to produce clean burning fuels for uses other than electricity generation would not be considered gasification. Consequently, these processes would be ineligible for exclusion from the definition of waste transformation. Gasification processes that use small amounts of oxygen or air internally as a reactant to generate the heat necessary for gasification would also be excluded. Confusion also exists in literature regarding the definitions of “incineration” and “combustion.” For these reasons, separate definitions were developed and clearly described for the processes covered under this report.

Conversion of organic material can proceed along three main pathways:

- Thermochemical
- Biochemical
- Physicochemical

Thermochemical Conversion Pathways

Thermochemical conversion is characterized by higher temperatures and conversion rates than most other processes. Thermochemical conversion includes a continuum of processes ranging from thermal decomposition in a primarily non-reactive environment (commonly called pyrolysis) to decomposition in a chemically reactive environment (usually called gasification if the products are primarily fuel gases or complete combustion if the products are fully oxidized). Pyrolysis can be considered an incomplete gasification process, in which a mixture of gaseous, liquid and solid products is produced, each of which may have some immediate use to sustain the process. The characteristics of each of these processes can also vary depending on the oxidizing or reducing media, process temperature and process pressure.

Combustion Definition

Combustion is the oxidation of the fuel for the production of heat at elevated temperatures without generating commercially useful intermediate fuel gases, liquids, or solids. Combustion of MSW or other secondary materials is generally referred to as incineration. Flame temperatures range typically between 1500 and 3000ºF depending on fuel, oxidant, stoichiometry, furnace design, and system heat loss. Particle temperatures in heterogeneous (e.g. unsteady reactions between solid and gas phases) combustion can differ from the surrounding gas temperatures, depending on radiation heat transfer conditions.

Combustion of solids involves the simultaneous processes of heat and mass transport, progressive pyrolysis, gasification, ignition, and burning, with no intermediate steps and with an unsteady, sometimes turbulent, fluid flow. Normally, combustion employs an excess of oxidizer to ensure maximum fuel conversion, but it can also occur under fuel-rich conditions. Products of combustion processes include heat, oxidized species (e.g. carbon dioxide [CO_2], water [H_2O]), products of incomplete combustion and other reaction products (mostly as pollutants), and ash. Other processes, such as supercritical water oxidation and electrochemical oxidation can produce similar end products at lower temperatures but higher pressures.

Gasification Definition

Gasification typically refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H_2, methane, and lighter hydrocarbons in association with CO_2 and N_2 depending on the process used. Alternative configurations using either indirect heating methods such as externally fired burners or autothermal methods using exothermic reducing reactions have been demonstrated.

While gasification processes vary considerably, typically gasifiers operate from 1300º F and higher and from atmospheric pressure to five atmospheres or higher. The process is generally optimized to produce fuel or feedstock gases. Gasification processes also produce a solid residue as a char, ash, or slag. The product fuel gases, including hydrogen, can be used in internal and external combustion engines, fuel cells, and other prime movers for heat and mechanical or electrical power. Gasification products can be used to produce methanol, Fischer-Tropsch (FT) liquids, and other fuel liquids and chemicals (see Chapter 4).

Gasification of solids with subsequent combustion of the gasification-derived fuel gases generates the same categories of products as direct combustion of solids, but pollution control and conversion efficiencies may be improved. Alternatively, the produced synthesis gases can be used directly for liquid fuel or chemical synthesis, eliminating or delaying the combustion process and the emission of resulting effluent.

Pyrolysis Definition

Pyrolysis is a process similar to gasification except generally optimized for the production of fuel liquids (pyrolysis oils) that can be used straight (e.g. as boiler fuel) or refined for higher quality uses such as engine fuels, chemicals, adhesives, and other products. Pyrolysis also produces fuel gases, and the solid residue contains most of the inorganic portion of the feedstock as well as large amounts of solid carbon or char.

Usually, a process that thermochemically degrades material without the addition of any air or oxygen is considered pyrolysis. Pyrolysis typically occurs at temperatures in the range of 750-1500^{o} F. Pyrolysis and combustion of pyrolysis-derived fuel liquids and gases also produce the same categories of end products as direct combustion of solids. Like gasification, their pollution control and conversion efficiencies may be improved. Where fuel liquids are produced, the eventual emission of combustion products may be considerably displaced from the source of fuel production (e.g., vehicle emissions).

Plasma arc and radio frequency (or microwave) heating refer to specific devices providing heat from electricity for gasification, pyrolysis, or combustion depending on the amount of reactive oxygen, hydrogen, steam, or other reactant fed to the reactor. Plasma arc processes use electricity passing through electrodes to produce a discharge converting the surrounding gas to an ionized gas or plasma. Gases heated in plasmas typically reach temperatures of 7000^{o} F and higher.

Catalytic cracking is a thermochemical process that employs catalysts using hydrogen-driven reducing reactions to accelerate the breakdown of high molecular weight compounds (e.g. plastics) into smaller products for the purposes of improving selectivity and imparting certain desirable characteristics to the final product, such as volatility and flashpoint of liquid fuels. This cracking process is often employed in oil refinery operations to produce lower molecular weight hydrocarbon fuels from waste feedstocks. These include gasoline from heavier oils, distillation residuals, and waste plastic.

Biochemical Conversion Pathways

Biochemical conversion proceeds at lower temperatures and lower reaction rates and can offer high selectivity for products. Higher moisture feedstocks are generally good candidates for biochemical processes. Non-biodegradable organic feedstocks, such as most plastics, are not convertible by biochemical processes.

Anaerobic Digestion Definition

Anaerobic digestion is a bacterial fermentation process that is sometimes employed in wastewater treatment for sludge degradation and stabilization. This is also the principal process occurring in the decomposition of food wastes and other biomass in landfills. Anaerobic digestion operates without free oxygen and results in a fuel gas called biogas, containing mostly CH_4 and CO_2 but frequently carrying other substances such as moisture, hydrogen sulfide (H_2S), and particulate matter that are generally removed prior to use of the biogas.

Anaerobic digestion is known to occur over a wide temperature range from 50 to 160º F. Anaerobic digestion requires attention to the nutritional needs and the maintenance of reasonable temperatures for the facultative and methanogenic bacteria degrading the waste substrates. The carbon/nitrogen (C/N) ratio of the feedstock is especially important. Biogas can be used after appropriate gas cleanup as a fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, and the manufacturing of chemicals. Anaerobic digestion is also being explored as a route for direct conversion to hydrogen

Aerobic Processing Definition

Aerobic conversion includes most commercial composting and activated sludge wastewater treatment processes. Aerobic conversion uses air or oxygen to support the metabolism of the aerobic microorganisms degrading the substrate. Nutritional considerations are also important to the proper functioning of aerobic processes. Aerobic processes operate at much higher reaction rates than anaerobic processes and produce more cell mass, but generally do not produce useful fuel gases. Aerobic decomposition can occur from as low as near freezing to about 160º F.

Fermentation Definition

Fermentation is generally used industrially to convert substrates such as glucose to ethanol for use in beverage, fuel, and chemical applications and to other chemicals (e.g., lactic acid used in producing renewable plastics) and products (e.g., enzymes for detergents). Strictly speaking, fermentation is an enzymatically controlled anaerobic process although the term is sometimes more loosely applied to include aerobic processing as well.

Fermentation feedstocks require pretreatment by chemical, physical, or biological means to open up the structure of biomass and reduce the complex carbohydrates to simple sugars. This set of pretreatments is often referred to as hydrolysis. The resulting sugars can then be fermented by the yeast and bacteria employed in the process. Feedstocks high in starch and sugar are most easily hydrolyzed. Cellulosic feedstocks, including the major fraction of organics in MSW, are more difficult to hydrolyze, requiring more extensive pretreatment.

Ethanol and carbon dioxide are the primary products of glucose fermentation by yeast. Ethanol inhibits microbial growth and fermentation, often essentially halting the fermentation when the ethanol concentration reaches about 12 percent. Ethanol must be removed from the fermentation broth to be used as fuel.

Processes are also in development that would convert ethanol to hydrogen without distillation. Although ethanol fermentation and anaerobic digestion are commonly classified separately, both are fermentation. Lignin in biomass is resistant to fermentation. Process residuals are typically considered for compost, boiler fuel, animal feed, or as a feedstock for thermochemical conversion to other fuels and products.

A summary schematic of thermochemical and biochemical processing of MSW is presented in Figure ES-1.

Physicochemical Conversion Pathways

Physicochemical conversion involves the synthesis of products using physical and chemical processing at near-ambient temperatures and pressures. It is primarily associated with the transformation of fresh or used vegetable oils, animal fats, greases, tallow, and other suitable feedstocks into useful liquid fuels and chemicals such as biodiesel, frequently by transesterification, a reaction of an organic glyceride with alcohol in the presence of catalyst.

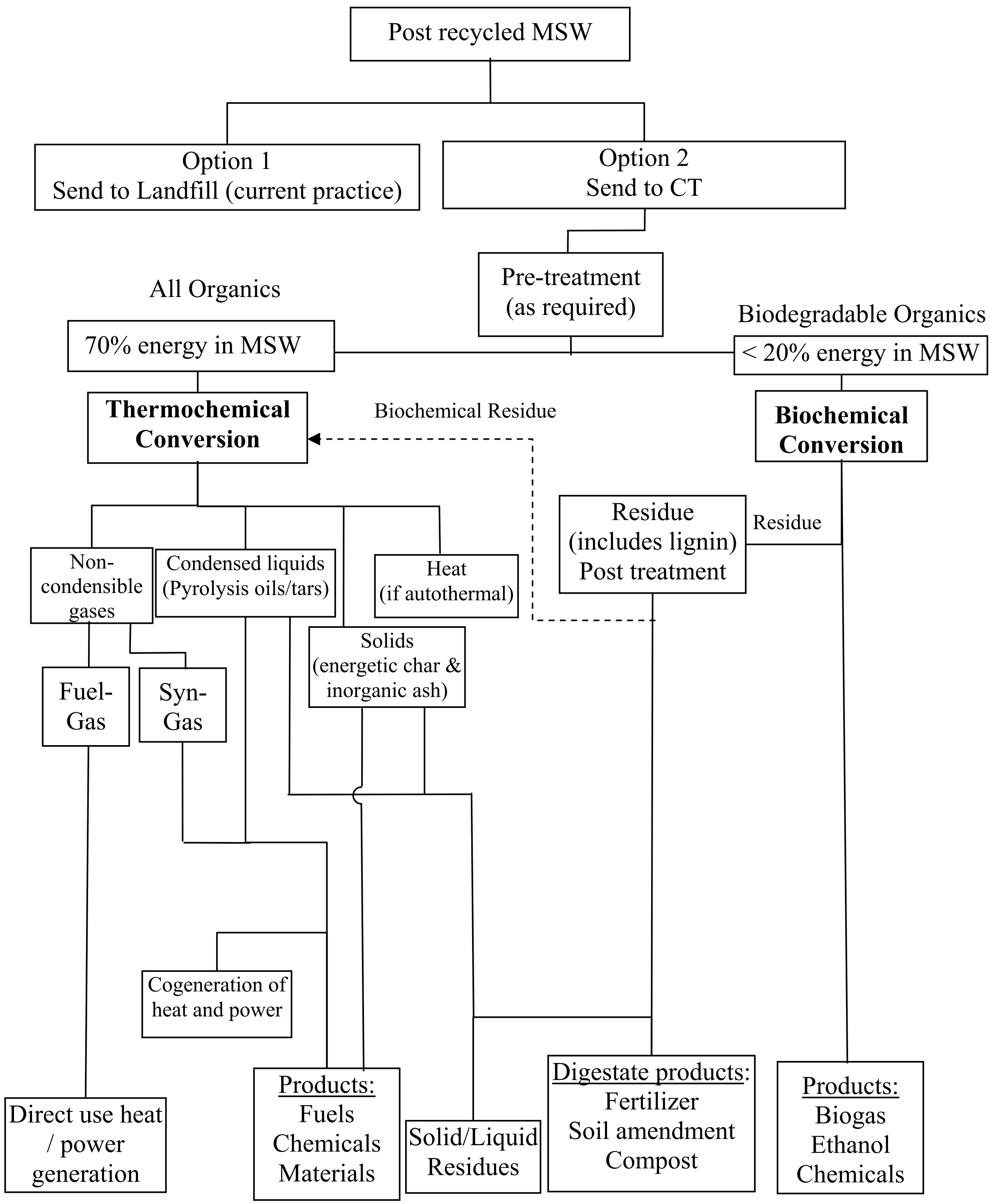

Figure ES - 1: A General Schematic of the Flows and Products from Processing Post-recycled MSW with Conversion Technologies.

Feedstocks

Feedstocks that can be utilized with conversion processes are primarily the organic materials now being landfilled (here, organic means "containing carbon and hydrogen"). These include paper, cardboard, plastic, food waste, green waste, and other waste. A summary of the waste material currently being landfilled, including the potential chemical energy of each component, is provided in Table ES-1.[†]

Thermochemical processes can potentially convert all the organic portion of the waste stream that is currently going to landfill into heat and other useful products. Because most thermochemical processes operate at elevated temperatures, the fate of trace inorganic elements, such as metals that may be present in MSW, needs to be considered in the process design. Some further sorting and/or processing of post-materials recovery facility (MRF) MSW would normally be conducted prior to thermal conversion to reduce particle sizes to those compatible with the process, and dry the material if needed.

Another element of the sorting process would be to remove, to the extent possible, materials such as PVC, batteries, or feedstocks with copper (Cu) that can contribute to the formation of toxic emissions. Metals, glass, and ash do not contribute substantially to energy value in thermochemical processing but may be substantially transformed due to the high temperatures involved. Plastics are also converted by thermochemical processing.

Biochemical processes can convert only the biodegradable fraction of feedstocks. Metals, glass, mineral matter, and most of the current waste plastic stream are inert to biodegradation. Some of the newer plastics include biodegradable fractions or are fully biodegradable. The fraction of these plastics in the waste stream is currently very small but may increase over time. Higher-moisture feedstocks tend to be good candidates for biochemical processes, partly because of the extra energy required for drying before use in most thermochemical processes.

Biochemical conversion technologies prefer source-separated green or food waste, or the biogenic fraction of mixed MSW after sorting. Some biochemical systems (so-called "high solids" reactors) can accept unsorted MSW (shredded or crushed to appropriate size) in the reactor, though this is suboptimal from the standpoint of material handling, reactor volume utilization, and disposal or use of residuals.

Paper and cardboard is the largest category of materials (on both a mass and energy basis) currently landfilled that could be processed by conversion technologies. Paper and cardboard material comprise 11 million tons or 30 percent of the materials currently landfilled. On an energy basis, paper/cardboard represents nearly half (44 percent) of the potential chemical energy in the waste stream. Although recycling of old corrugated containers (OCC) and old newspaper (ONP) materials is a well developed industry in California, the recycling rates for these components are still only 52 and 58 percent, respectively.

[†] This summary of the landfilled waste stream in California uses 2003 disposal amounts and 1999 waste characterization data. The CIWMB is currently updating the statewide landfilled waste characterization.

Table ES-1. California Annual Landfilled Waste Stream Characterization with Estimated Chemical Energy Content by Component[1]

	Landfilled[a,d] (million tons)	Fraction of Total[d] (% wt.)	Moisture[b] (%wb)	Landfilled (million tons, dry)	Ash / mineral matter (million tons)	HHV [b] (BTU/dry lb)	Potential Chemical Energy (PJ)[c]	Equivalent barrels of crude oil (millions)	Potential Chemical Energy: Fraction of total (%)	Potential Chemical Energy: (rank)
Paper/Cardboard	11.3	30.3	10	10.2	0.60	7650	164	27	44.2	1
Food	5.9	15.7	70	1.8	0.29	6000	22	4	6.0	5
Leaves and Grass	3.0	7.9	60	1.2	0.12	6450	16	3	4.4	7
Other Organics	2.6	6.9	4	2.5	0.26	3800	20	3	5.4	6
C&D Lumber	1.8	4.9	12	1.6	0.09	8300	28	5	7.5	4
Prunings, trimmings, branches and stumps	0.9	2.3	40	0.5	0.03	8175	9	1	2.5	9
Biomass Components of MSW Total	**25.5**	**68.0**		**17.8**	**1.4**		**261**	**42**	**70.0**	
All non-Film Plastic	1.9	5.0	0.2	1.9	0.04	9475	38	6	10.2	3
Film Plastic	1.5	3.9	0.2	1.5	0.04	19400	59	10	16.5	2
Textiles	0.8	2.1	10	0.7	0.06	8325	13	2	3.4	8
Non-Biomass Organic Components of MSW Total	**4.1**	**11.0**		**4.0**	**0.14**		**110**	**18**	**30.0**	
Other C&D	2.5	6.7		2.5	2.5	-				
Metal	2.3	6.1		2.3	2.3	-				
Other Mixed and Mineralized	2.0	5.3		2.0	2.0	-				
Glass	1.1	2.9		1.1	1.1	-				
Inorganic Components of MSW Total	**7.8**	**20.9**		**7.8**	**7.8**	**0**	**0**	**0**	**0**	
Totals (1999)[d]	**37.4**	**100**		**29.7**	**9.4**	**(ave.)**	**370**	**60**	**100**	
Estimate for 2003[d]	**39.8**			**31.6**	**10.0**	**5900**	**394**	**64**		

a) California waste stream composite data (http://www.ciwmb.ca.gov/WasteChar/Study1999/OverTabl.htm), Accessed 3 May, 2004
& California Solid Waste Generation and Diversion (http://www.ciwmb.ca.gov/lgcentral/Rates/Diversion/RateTable.htm) Accessed 3 May, 2004
b) Adapted from Tchobanalglous, G., Theisen, H. and Vigil, S.(1993),"Integrated Solid Waste Management", Chapter 4, McGraw-Hill, New York
& Themelis, N. J., Kim, Y. H., and Brady, M. H. (2002). "Energy recovery from New York City municipal solid wastes." Waste Management & Research, 20(3), 223-233
c)100 PJ/yr is equivalent to 3.2 GW of chemical energy used continuously throughout the year
d) The latest Waste characterization data publicly available is from 1999. Potential Energy in 2003 disposal was estimated using the 1999 characterization. CIWMB is currently conducting a new characterization of the disposed waste stream and can be used in the 2003 energy estimate when available.

The collection of materials is a consideration with recycling of OCC and ONP, including the problem of capturing OCC from small businesses. Mixed paper is also recycled, though the value of mixed paper as a commodity has been historically relatively low. More recently, the export market, particularly to China, has resulted in significantly higher prices paid for mixed paper grades. Overall, the paper and cardboard recycling rate in California is slightly higher than 30 percent, or 4.5 million tons of material. Increase in demand for paper for recycling will depend on new efforts by government and the private sector to utilize products made with a higher percentage of recycled-paper content.

From an energy standpoint, plastics and other organic components of fossil origin in MSW are the second-largest component of the waste stream, representing some 30 percent of the chemical energy. On a weight basis, plastics and textiles represent 11 percent or 4.2 million tons of material landfilled. On a volumetric basis, plastic materials occupy as much as 22 percent of the space in a landfill due to their comparatively lower density. Plastic materials present in the waste stream in the highest amounts include high-density polyethylene (HDPE), polyethylene terephthalate (PET), film plastics, and other durable plastics.

Although some plastic recycling markets are well developed, the overall recovery fraction of plastics is only about 5 percent. PET bottles have the highest recycling rate at approximately 35 percent. HDPE containers are the next-highest category of recycled plastics with a rate of 13 percent. The cost of collecting and processing waste plastics typically exceeds the value of the material. The number of new plastic containers has also increased in recent years, resulting in corresponding decreases in the overall recycling rate even though the total amount recycled has increased.

With a high percentage of the total available chemical energy in mixed MSW, non-recycled plastics could be attractive materials for conversion processes. Thermochemical processes currently represent the only means for plastics conversion. With the appropriate thermochemical processes, gasoline, diesel, and other fuels could be produced as well as petroleum-like base products such as ethylene for new plastics production. These would displace fossil petroleum use.

Thermochemical techniques have previously been developed for plastics recycling. These conversion technologies could also be applied to the growing problem areas of electronic components, consumer appliances, and plastic packaging materials. Since chlorine is a precursor to dioxin formation, the chlorinated plastics components (PVC) would either have to be separated from the feed stream or include appropriate remediation technology in the process.

Primary feedstocks for biochemical processes would be green and food wastes, although other biomass could also be used. Lignin is largely undegraded in most fermentation systems, including anaerobic digestion and hence remains as a residue of the process. Lignin represents approximately 28 percent of typical softwood, up to 50 percent for nut shells, with lower percentages for grasses, straws, and other herbaceous materials. Paper is primarily cellulose but may be coated or otherwise treated and include other constituents such as clay and heavy metals from pigments. Sludge products may have value as fertilizer or soil additives if heavy metal concentrations can be kept sufficiently low. The lower temperatures of biochemical treatment have some advantages in terms of reducing the potential formation of pollutant and hazardous species compared with higher temperature thermal processes, but cannot process the full waste stream.

Thermochemical Process Descriptions and Current Status

Pyrolysis and gasification systems tend to employ several common steps, although system designs vary by manufacturer. These steps include feedstock preparation and introduction into the reactor, the reaction of the waste through application of heat or addition of other reactants such as air, oxygen, steam, hydrogen, post combustion or processing of the gases produced during the reaction step, and the management of the resulting liquids, char, and ash.

Schematic diagrams of pyrolysis and gasification processes are shown in Figures ES-2 and ES-3. Since a number of gasification systems incorporate pyrolysis units prior to the gasification unit, the general gasification schematic includes an upfront pyrolysis unit in addition to the main gasification reactor but this may not always be present.

The preparation and means of introducing the feedstock into the reactor depend on the specific nature of the waste being processed. Shredding or size reduction is often used to facilitate handling and help promote the reaction of the feedstock in the pyrolyzer or gasifier. Drying of the feedstock is also needed for some processes, although the degree of drying is process-dependent. Some processes are capable of handling moist/undried MSW or other waste while others require dry feedstock. Introduction of the feedstock in the form of an aqueous slurry is possible in some processes.

For MSW, an additional processing step is often used to recover inert and recyclable materials such as metal and glass that will not react in the gasification or pyrolysis processes. Upstream separation of certain plastics and paper would probably also be used to recover any potentially recyclable material before the reactor. Upstream sorting processes can also be used for the removal of green waste and other moist organics in order to provide a feedstock with lower moisture content. Sorted MSW can also be pelletized or otherwise densified into a refuse-derived fuel (RDF).

The reaction vessel itself is one of the most variable components of the system design. Reactors can typically be characterized as either vertical or horizontal. A rotary kiln is an example of a horizontal reactor. The three main types of vertical reactors are fixed bed, fluidized bed, and entrained bed. For the fixed bed systems, the feedstock is typically fed onto a grate with either up-, down-, or cross-draft flow of gases. In practice the bed is not usually actually fixed, but moves through the system either by active or passive (e.g. settling) processes.

In an updraft flow or countercurrent reactor, the air or oxygen supply is injected from the bottom, the feed from the top, and the product gases are extracted from the top of the reactor vessel while the solids move downward to be removed through the grate. In a downdraft, co-current flow reactor, the air generally enters near the top of the reactor along with the feed and products are extracted near the bottom of the reactor.

In a fluidized bed reactor, the reactor bed consists of inert particles (usually sand or alumina) sometimes containing a catalyst. Gas or air introduced below the bed causes the particles to become suspended, making the reactor contents behave like a liquid. Feedstock can be fed directly into the bed or introduced above the bed. The feedstock and bed particles undergo continuous agitation and mixing during the process to provide a more uniform temperature distribution and improved heat transfer. In a bubbling bed reactor, the oxygen, air, steam, or other carrier or reactant fluid used to fluidize the bed is injected at a velocity that is high enough to suspend the bulk of the solids on the gas until the feedstock particle size has become sufficiently small due to reaction. In a circulating fluidized bed, the gas velocity is increased so as to entrain a large fraction of the bed with subsequent active removal and recirculation of bed particles producing a more uniform distribution throughout the reactor. Other reactor designs include open hearth, tubular and cylindrical tank reactors.

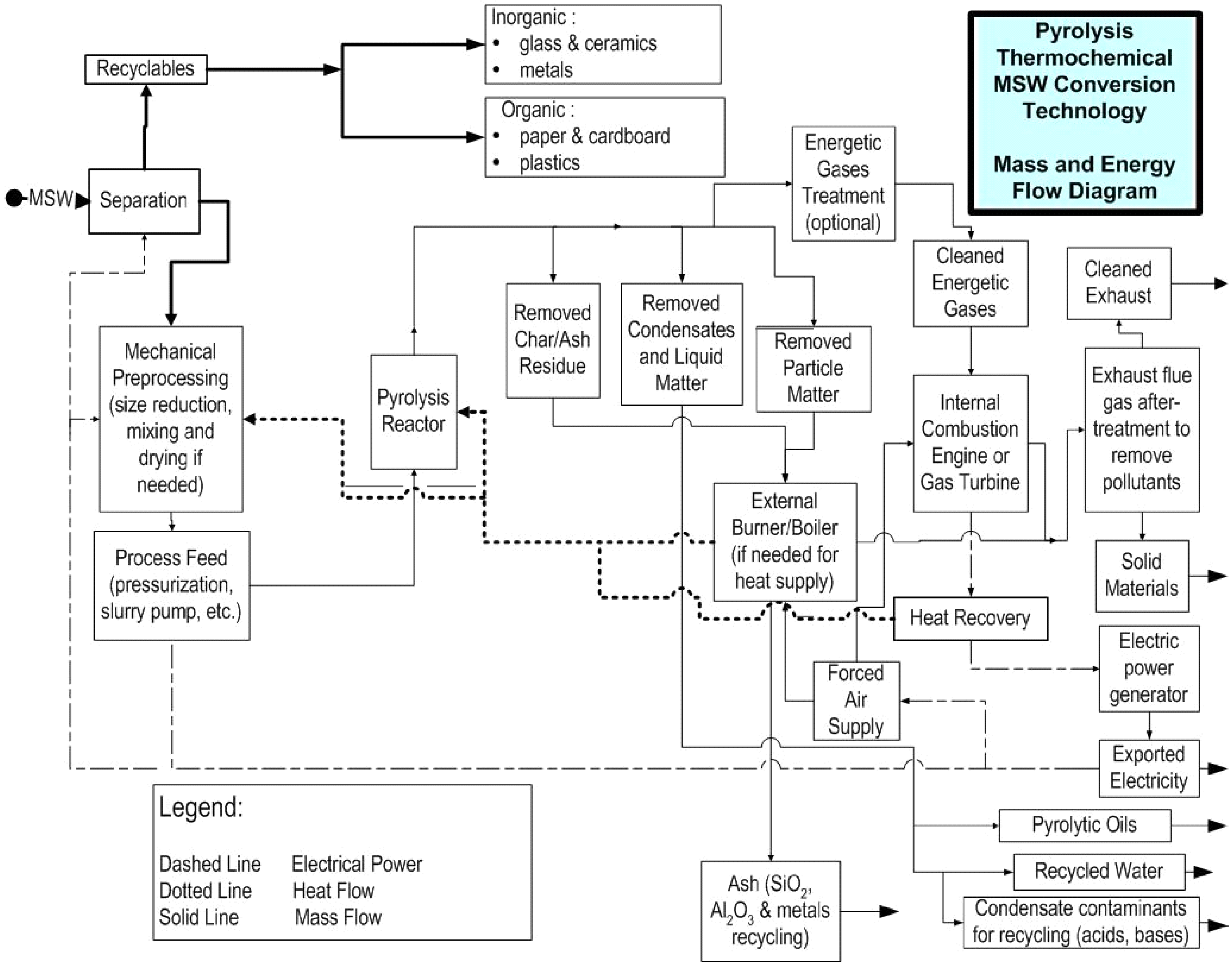

Fig. ES - 2: Schematic Diagram of a Pyrolysis Process.

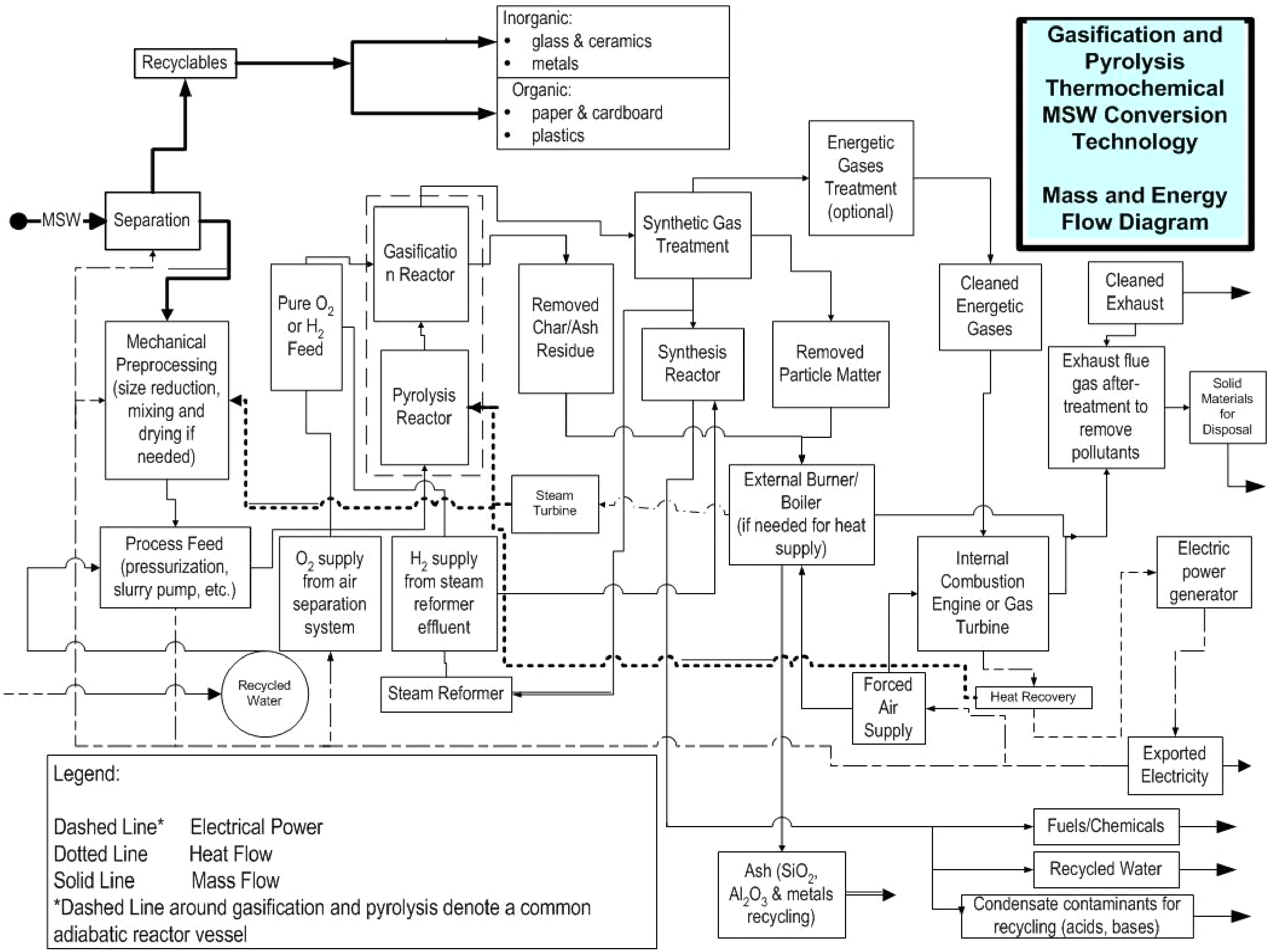

Fig. ES - 3: Schematic Diagram of Gasification Process with Front End Pyrolysis Process.

The composition of the pyrolytic/gasification products can be changed by the temperature, the pressure, the speed of the process, and the rate of heat transfer. Lower pyrolysis temperatures usually produce more liquid products and high temperatures produce more gases. Slow pyrolysis, also called carbonization, can be used to maximize the yield of solid char. This process requires a slow pyrolytic decomposition at low temperatures. A common example of this method of pyrolysis is the production of charcoal from wood.

The pyrolyzing/gasifying media can also be varied by using hydrogen and/or steam, in which case significant differences in the product distribution can occur. Such processes are currently at a research level for application to wastes, but have been investigated in greater detail for the processing of coal. Hydrogen gas can be used to enhance chemical reduction and suppress oxidation from the elemental oxygen in the feedstock. This process, known as hydropyrolysis, was originally developed to enhance the production of fuel gases from the pyrolysis of coal. Water or steam can also be incorporated into the thermochemical process to change the resultant gases and vapors and increase the porosity of the resultant char. By creating a very high surface area and porosity, activated carbon (charcoal) can be formed. Steam pyrolysis or gasification can also be used to achieve adequate results at lower temperatures but at higher pressures than processes conducted in the absence of water (so called 'dry processes'). This ability to pyrolyze and gasify wet streams of carbonaceous material using chemically reducing processes appears to have some distinct advantages over the more traditional dry and partially oxidative methods. Most biomass materials usually contain between 25 percent and 45 percent by mass (weight) of elemental oxygen, so some oxidative reactions will occur during pyrolysis, even though additional oxygen is intentionally excluded from the process.

Plasma arc and radio frequency, or microwave heating, are techniques for providing heat from electricity for gasification, pyrolysis, or combustion depending on the amount of reactive oxygen or hydrogen fed to the reactor. Very high temperatures are created in the ionized plasma. The electric arc creates a plasma at temperatures of 7000º F and higher. The non-ionized gases in the reactor chamber can reach 1700–2200º F. The molten slag is typically around 3000º F. Plasma arc heating can provide advantages in controlling the combustion process, but at the same time there are efficiency losses due to the need to produce electricity to provide process heat. As a result of this inefficiency, plasma arc technologies were developed for specialized or hazardous feedstocks such as contaminated soils, low-level radioactive waste, and medical waste.

Catalytic cracking is a thermochemical conversion process usually applied to polymeric wastes (e.g. plastics) to produce liquid fuels (primarily gasoline). The addition of catalysts to enhance the rate of this thermochemical method has created many proprietary commercial implementations. However, the deactivation of these catalysts by the chlorine present in PVC plastics makes the general application of this technology problematic without extensive sorting and pre-treatment of the plastic from the MSW stream. The use of catalytic cracking to convert waste plastics into fuels is well established within oil refinery complexes worldwide. A catalytic cracking process is shown schematically in Figure ES-4.

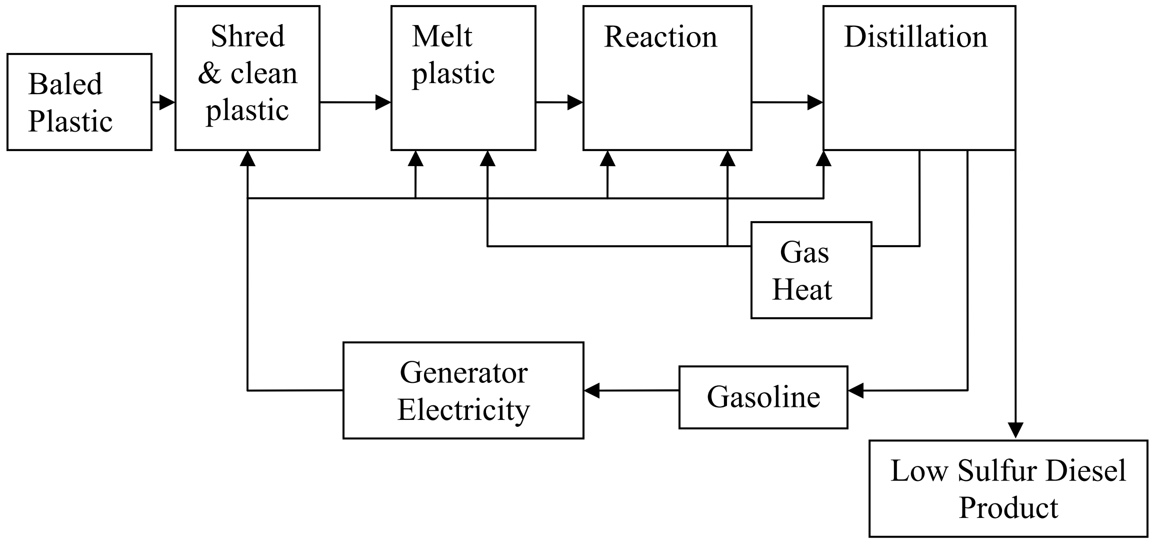

Fig. ES - 4: Schematic of a Catalytic Cracking Process using Plastic Feedstocks.

The product gases and vapors produced during the thermochemical reaction are often combusted in a separate combustion chamber that immediately follows the reactor. The thermal energy resulting from the combustion of these gaseous products can be used in a variety of ways, including steam for electricity production and heat for the pyrolysis reactor or for feedstock drying.

An important component of any combustion process is the pollution control equipment used to clean the effluent gases before exhausting to the atmosphere. The combustion of pyrolytic or gasification product gases is more efficient and produces fewer emissions than straight combustion of solid waste materials. However, emissions from gas combustion products in thermochemical processes still require emissions control to meet regulatory standards. Standard exhaust flue gas control strategies for combustion processes include particulate filters or bag houses, wet scrubber techniques, electrostatic precipitation and a number of other techniques.

Current Status of Thermochemical Processes

Gasification dates to the mid-1800s, when the technique was heavily used in the industrialization of Europe. Early gasification processes were largely developed for coal. Early advances in gasification included the Winkler fluid bed process, the Lurgi process, and the Koppers-Totzek suspension gasification process. After World War II, the use of gasification declined as petroleum became more available. In the 1970s and 1980s, several facilities began operating for production of synthetic fuels, and these remain the largest application of gasification. In the 1980s, the United States, Europe and Japan began to increase the development and deployment of gasification and pyrolysis techniques for waste. Prior to 1990, several facilities using unsorted MSW were abandoned due to technical problems related mostly to feedstock quality and handling.

A large number of gasification and pyrolysis technologies have been developed and demonstrated on levels from laboratory scale through pilot and fully commercial scale. Coal remains the predominant feedstock that is gasified, but the commercialization of gasification for waste is growing. In general, most of the commercially identified pyrolysis and gasification facilities are operational at a level of between 100 and 500 tons per day (TPD) capacity.* In total, over 40 pyrolysis or gasification facilities commercially processing MSW were identified. The four largest technologies alone represent processing capacities of more than 2.5 million tons of MSW each year.

The use of pyrolysis and gasification for MSW has mostly been applied in Japan where landfill space and resources are limited. In examining the three largest suppliers in Japan, the capacities of their plants represent more than two million tons of material each year, with additional plants being planned. Much of this capacity has been installed in the past five years. Nippon Steel is the largest supplier with a capacity of more than 1.2 million tons of waste with more than 20 facilities. Ebara, Mitsui-Babcock, and Thermoselect/JFE operate several facilities with each company having a capacity near 400,000 TPY. Ebara is scheduled to commission a 1,500 TPD facility in Kuala Lumpur, Malaysia, in May 2006. Hitachi Metals has commissioned a 300 TPD plasma arc gasification facility in Utashinai City, Japan, with several other smaller facilities. These facilities process MSW or MSW with auto shredder residue (ASR). A number of other technologies are marketing and commercializing technologies in Japan including Hitachi-Zosen, NKK, Suminito, Kobe Steel, MHI, and IHI.

In Europe, a limited number of pyrolysis facilities are operating at a scale above 50,000 TPY for MSW or other general wastes, although a number of vendors indicated plans for development of facilities at that scale. For gasification in Europe, the SVZ facility at Schwarze Pumpe in Germany is one of the largest facilities with a capacity of 450,000 TPY of solid waste and 55,000 TPY of liquid waste. The Thermoselect Karlsruhe facility also has a capacity of over 200,000 TPY. A facility in Burgau, Germany, has been operating at 40,000 TPY since 1987. Other companies with commercially operating facilities or facilities that have operated commercially include Thide-Environmental, Serpac Environmental, Graveson Energy Management, Foster Wheeler, Emerkem, PKA, Pyromex, and Compact Power.

There are other gasification facilities operating on a smaller level or in the planning stages in Europe. These appear to be primarily niche applications or in areas where projects were supported by public agencies. The use of gasification for the processing of coal is more widely applied, and much of this technology can be utilized for processing MSW although reactor designs for MSW and biomass may be optimized differently from those designed for coal. This includes the designs by TyssenKrupp Uhde, which has over 100 gasifiers in place primarily for coal.

Several facilities in California or nearby states are operating at a small scale or are being commissioned at a larger scale including a 50 TPD thermochemical facility recently constructed by International Environmental Solutions (IES) in Romoland, California. This facility is designed for use with a wide range of feedstocks including medical waste, fireworks, MSW, bark beetle infested trees, dried sewage sludge, and tires, all of which will be tested as part of their air permitting process. Primary feedstocks planned for actual operation will include pretreated medical waste, electronic waste, bark beetle infestation trees, and fireworks. North American Power operates a similar facility in Las Vegas, Nevada. This facility is capable of processing a range of feedstocks including MSW, tires, industrial and medical waste, and liquid sludges. A catalytic cracking facility is also being planned in Hanford, California, for the processing of 50

* Note that some facilities report capacities in tons per day and some in tons per year. For reference, 100 TPD corresponds to 36,500 TPY for continuous 24 hour/7 days a week operation or between 31,000 and 33,000 TPY for a more typical operation at 85-90% of capacity.

TPD of mixed plastic waste with another 50 TPD of capacity planned for a second stage. Pyromex AG is also actively promoting its technology in North America and California through its representative Innovative Logistics Solutions, Inc. (ILS) of Palm Desert, California. ILS currently has projects for a 400 TPD ASR facility in Anaheim, California, and a 250 TPD green waste facility in Thousand Palms, California. Pryomex also has two active facilities in Europe processing sludge. Chateau Energy Group is refurbishing a power plant in El Centro that had previously used a Lurgi fluidized bed furnace. Chateau Energy is planning to use a plasma arc gasifier consuming tire derived fuel (TDF) and natural gas generating up to 45 MW_e.

Non-combustion thermochemical conversion processes for woody biomass and some energy crops have been implemented to some degree elsewhere in North America. The FERCO gasification process, developed by Battelle, operated a gasifier co-located with a wood-fired power station in Burlington, Vermont, in preparation for installing a gas turbine. Though the gasifier operated successfully, demonstration funding was exhausted before the gas turbine was installed. Manufacturing & Technology Conversion International, Inc., has demonstrated a gasification system that has been tested with RDF, sludges, and wood waste, but could also be used for ASR and presumably MSW. For wood waste applications, Ensyn, Dynamotive and Renewable Oil International are all marketing fast pyrolysis systems. Ensyn currently has six operating units ranging in size from 40 TPD to 70 TPD in Ontario and Wisconsin with two others under construction. Ensyn is also building a commercial demonstration facility in conjunction with Ivanhoe Energy near Bakersfield, California, for processing heavy crude oil components into more valuable light components. DynaMotive will be commissioning a 110 TPD unit in Ontario, Canada, for wood waste in fall of 2004.

Gasification technologies are used commercially in the processing of coal, petroleum and natural gas to produce synthesis gas. Biomass is also gasified for heat and power, mostly in Europe and East Asia at small scales compared with coal facilities. Up to 163 gasification facilities are expected to be operating globally by 2006 representing more than 37,000 MW_{th} capacity. In the U.S., the Dakota Gasification Co. has been operating a coal gasification facility that is one of the largest in the world since 1984. The Wabash River Gasification Project in Indiana and the Tampa Electric Polk Power Station Integrated Gasification Combined Cycle project both gasify coal and pet coke on a large scale to produce power. Both have been successful projects. Eastman Chemical in Kingsport, Tennessee has operated a coal gasification facility since 1984. The syngas is used to produce commercial chemicals (described below). The continuing expansion and maturity of gasification technology for other fuels is expected to provide a foundation that may lead to commercial scale MSW gasification in the U.S.

Several MSW conversion facilities have experienced technical or financial problems during the course of operation or commissioning. Siemens experienced considerable problems with the continuous operation of its Fürth Plant in Germany that culminated in a serious accident at the site. The accident was reportedly due to a plug of waste that formed in the pyrolysis chamber that resulted in an overpressure and escape of pyrolysis gas. European sources indicate that the problem was the result of processing full size mattresses, an issue that has been resolved in newer versions of the technology by addition of an up-front shredder. These problems caused Siemens to withdraw from the European market. A Thermoselect facility in Karlsruhe, Germany, had problems that led to considerable delays in commissioning. The 792 TPD facility was finally commissioned in 2001 and appears to have operated since then. Notwithstanding the issues with some early plants, both the Siemens technology and the Thermoselect technology have been widely applied at other facilities, so the technologies appear to be technologically sound and are among the most advanced in terms of commercialization.

A plant built by Brightstar Environmental in Wollongong, New South Wales, Australia has had problems with the char gasification component of the process and corresponding financial problems with the plant. Technological risks remain when using alternative thermochemical conversion technologies to process heterogeneous and highly variable feedstocks such as post-recycled MSW. Given the potentially large market size and the rapid progress toward commercialization during the past five years, especially in Japan, the technology appears to be well on its way to technological maturity in terms of efficiency and reliability.

Biochemical Conversion Process Descriptions and Current Status

Biochemical Conversion Process Descriptions

Biochemical conversion technologies operate at lower temperatures and lower reaction rates than thermochemical processes. The main biochemical processes are anaerobic digestion, aerobic digestion and composting, and fermentation.

Pretreatment for biochemical processes can be performed in a number of ways. Hydrolysis is a pretreatment step whereby cellulose and hemicellulose are hydrolyzed or broken down into simple sugars that can be fermented to ethanol or other products. Fermentation is strictly an anaerobic process, but aerobic processing can be involved to make enzymes needed for hydrolysis or for making some products such as polymers from sugars. Other pretreatment methods are based on lignin removal or disruption of hemicellulose or lignin or decrystallization of cellulose.

Digestion is a term usually applied to anaerobic mixed bacterial culture systems employed in many wastewater treatment facilities for sludge degradation and stabilization. Anaerobic digestion is also becoming more widely used in on-farm animal manure management systems, and is the principal process occurring in landfills that creates landfill gas (LFG). Anaerobic digestion operates without free oxygen and results in a fuel gas called biogas containing mostly methane (CH_4) and carbon dioxide (CO_2), but frequently carrying impurities such as moisture, hydrogen sulfide (H_2S), and particulate matter.

Biogas can be used after appropriate gas cleanup as a fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, or for the manufacturing of chemicals. Before landfilling, treatment or stabilization of biodegradable materials can be accomplished by a combination of anaerobic digestion followed by aerobic composting. Landfill bioreactor technology, which accelerates the rate of decomposition and improves LFG recovery and results in higher waste capacity than standard dry tomb landfills, is an emerging technology and may represent a substantial improvement over standard landfills.

Anaerobic digestion functions over a wide temperature range from the so-called psychrophilic temperature near 50º F to extreme thermophilic temperatures above 160º F. The temperature of the reaction has a very strong influence on the anaerobic activity, but there are two optimal temperature ranges in which microbial activity and biogas production rate are highest, the so-called mesophilic and thermophilic ranges. The mesophilic regime is associated with temperatures of about 95º F, the thermophilic regime of about 130º F. Operation at thermophilic temperature allows for shorter retention time and a higher biogas production rate, however, maintaining the high temperature generally requires an outside heat source because anaerobic bacteria do not generate sufficient heat. Aerobic composting can achieve relatively high temperatures (up to160 ºF) without heat addition because reaction rates for aerobic systems are much higher than those for anaerobic systems. If heat is not conducted away from the hot center of a compost pile, then thermochemical reactions can initiate which can lead to spontaneous combustion if sufficient oxygen reaches the hot areas. Managed compost operations use aeration to provide oxygen to the bacteria but also to transport heat out of the pile.

The anaerobic digestion of lignocellulosic waste occurs in a three-step process often termed hydrolysis, acetogenesis, and methanogenesis, as shown schematically in Figure ES-5. The molecular structure of the biodegradable portion of the waste that contains proteins and carbohydrates is first broken down through hydrolysis. The lipids are converted to volatile fatty acids and amino acids. Carbohydrates and proteins are hydrolyzed to sugars and amino acids. In acetogenesis, acid forming bacteria use these by-products to generate intermediary products such as propionate and butyrate. Further microbial action results in the degradation of these intermediary products into hydrogen and acetate. Methanogenic bacteria consume the hydrogen and acetate to produce methane and carbon dioxide. A schematic of a single stage anaerobic digestion process is provided in Figure ES-6.

Fermentation is used industrially to produce products such as ethanol for beverage, fuel, and chemical uses as well as other chemicals such as acetic acid and lactic acid by anaerobic organisms or enzymes, antibiotics, and other products by aerobic organisms. Although fermentation and anaerobic digestion are commonly classified separately, both are biochemical fermentation methods that produce different products. Hydrolysis is often used to pretreat lignocellulosic feedstocks to break down the cellulose and hemicellulose from the lignocellulose and break down the compounds into simple sugars. Hydrolysis can be catalyzed by use of acids (either strong or weak), enzymes, and/or hydrothermal means, the latter including hot water and supercritical methods. A schematic of a two-stage dilute acid hydrolysis process to produce sugars followed by fermentation is shown in Figure ES-7; a concentrated acid hydrolysis followed by fermentation is shown in Figure ES-8.

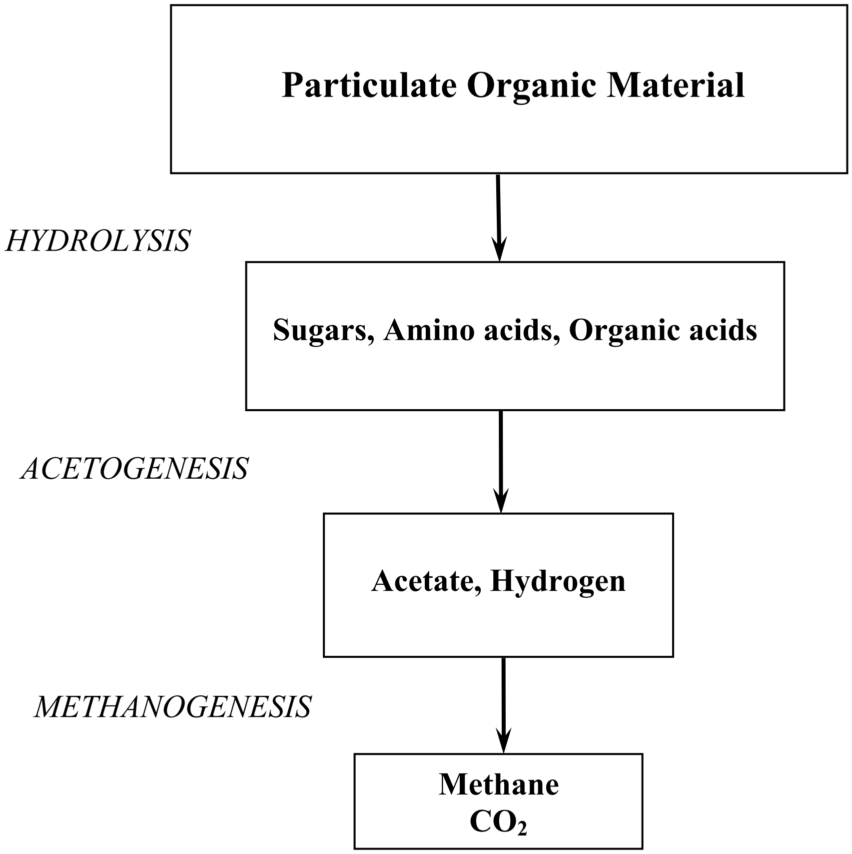

Fig.ES - 5: Anaerobic Digestion Block Diagram. Adapted from Gujer, W., and Zehnder, A. J. B. (1983). "Conversion processes in anaerobic digestion." ***Wat. Sci. Tech.*****, 15, 127-167.**

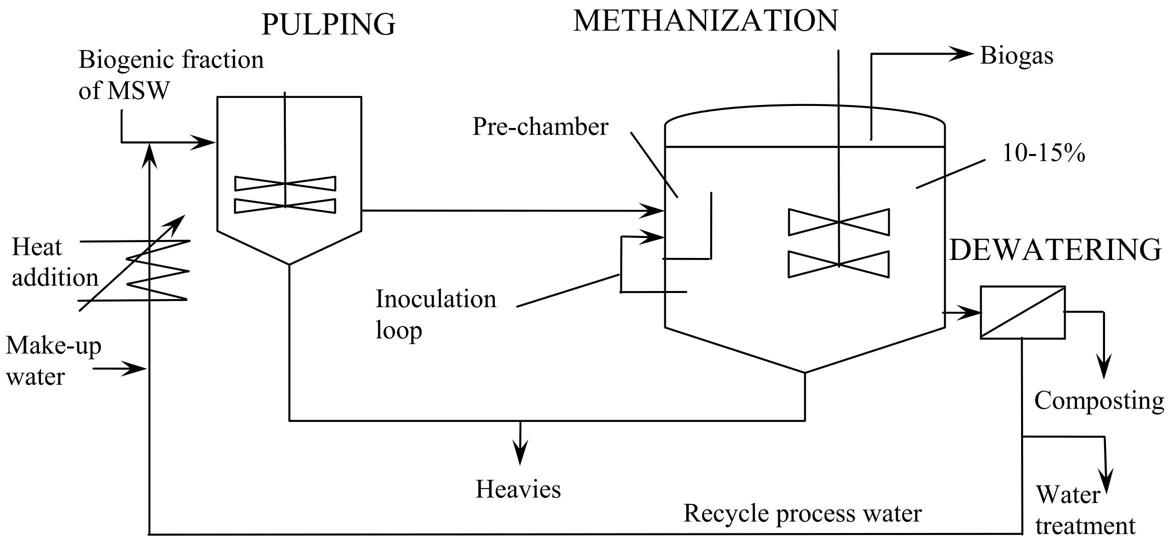

Fig. ES - 6: Schematic of Single-Stage Low Solids Anaerobic Digestion System. (Waasa, Finland)

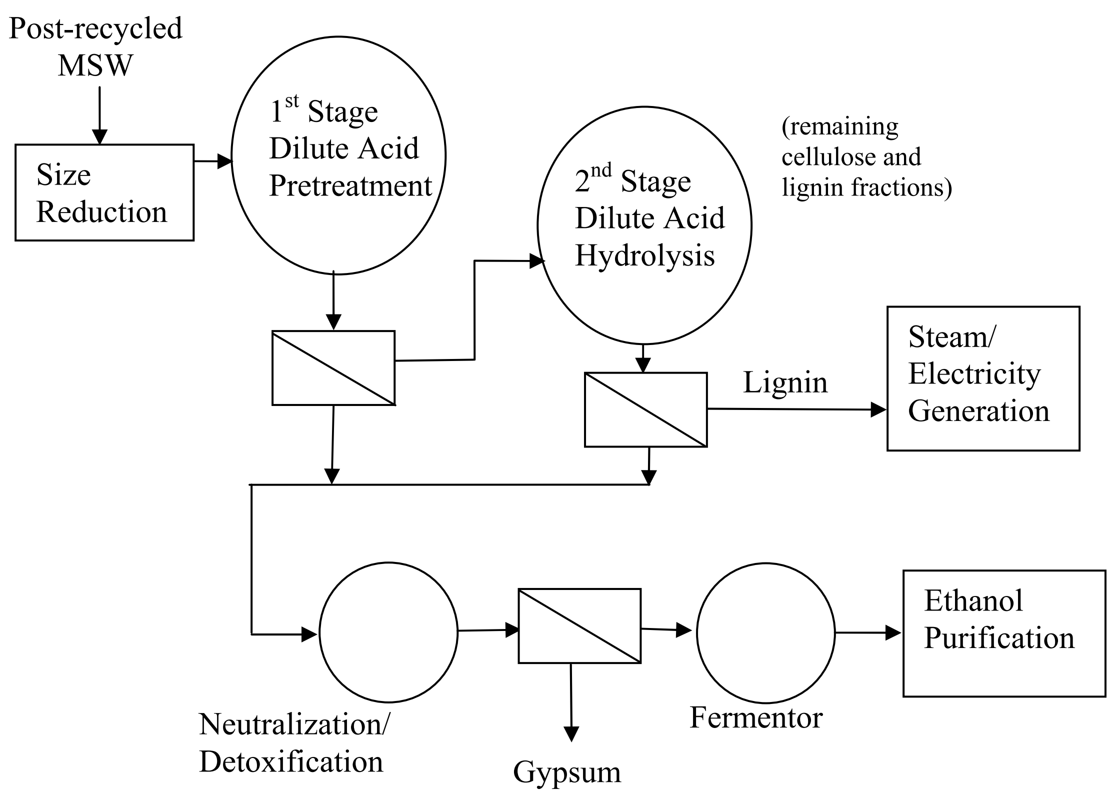

Fig. ES - 7: Schematic of Typical Two-Stage Dilute Acid Hydrolysis Fermentation.

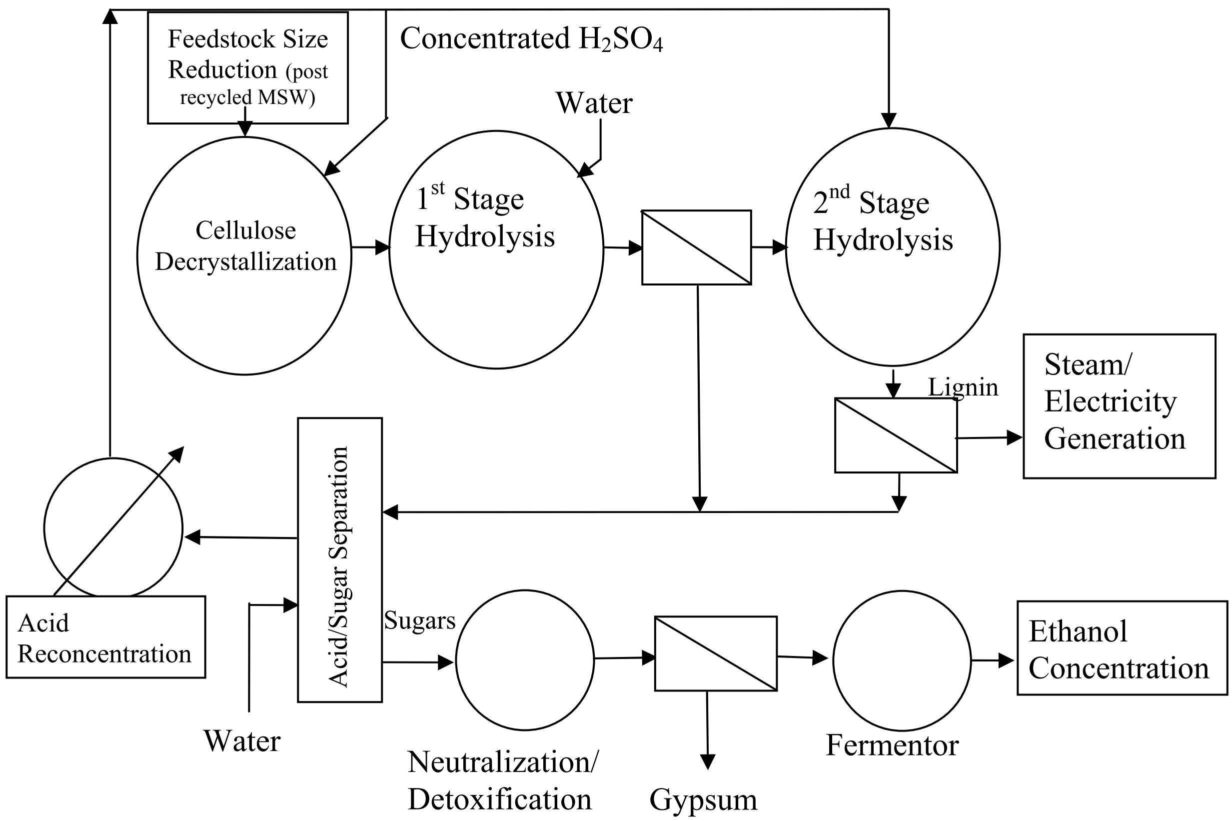

Fig. ES - 8: Schematic of Concentrated Acid Hydrolysis Fermentation. (Adapted from http://www.ott.doe.gov/biofuels/concentrated.html)

Ethanol can be produced once the complex molecules have been hydrolyzed and conditions made favorable (e.g., pH and temperature adjustment) for fermentation. A variety of microorganisms (bacteria, yeast, or fungi) can be employed, including recombinant organisms designed for higher productivity or specificity. Typically, 5 percent to 12 percent of the carbohydrate is converted to cell mass, which results in the most practical ethanol production processes converting no more than 46 percent of the fermented carbohydrate to ethanol. The remaining liquid broth is recycled or sent to a wastewater treatment facility for appropriate management. The lignin and other residual mass can be dried and used as compost, boiler fuel for electricity or steam production, or processed thermochemically into other fuels and chemicals. When fermenting starch materials, such as corn grain, high value feed co-products are produced. High value derivatives may also be possible from cellulosic feedstocks.

Aerobic digestion is a biochemical process for converting biogenic solid waste into a stable, humus-like product. Aerobic conversion uses air or oxygen to support the metabolism of the aerobic microorganisms degrading the substrate. Aerobic conversion includes composting and activated sludge wastewater treatment processes. Composting produces useful materials, such as mulch, soil additives and amendments, and fertilizers.

Current Status of Biochemical Processes

Anaerobic digestion systems using solid waste feedstocks are widely utilized in Europe. European Union (EU) policies have developed to minimize the amount of material being landfilled. These policies are driven by several factors including limited space for new landfills and the needs for methane emission reductions and increased renewable energy production under the Kyoto Protocol, to which the EU is a signatory. Examples of policies implemented to reduce material flow to landfill in Europe include Germany's Extended Producer Responsibility (EPR) approach, which requires manufacturers to be responsible for recovery of packaging material, and restrictions on the amount of biodegradable material that can be disposed in landfills. The result of waste management and energy policies, limited space, and high tipping fees in Europe are responsible in large part to growth of landfill alternatives including thermochemical and biochemical conversion systems.

Anaerobic digestion and/or aerobic composting of kitchen, food processor, and garden wastes is well established in Europe. To improve the quality of feedstocks used in anaerobic digestion (AD) and composting operations, source separation of household and commercial food and garden wastes is utilized extensively (at least 11 EU countries have implemented or are about to implement source separation for food and green wastes). In Switzerland, for example, approximately 220 lb per person per year of source separated food and green waste is collected. About 12 percent of the material is stabilized by AD facilities, and the balance is composted. Germany has more than 500 biochemical treatment facilities that process more than 8 million TPY of green and food wastes, with the majority being aerobic compost facilities.

There are more than 80 AD facilities in Europe with capacity greater than 3000 TPY using mandatory pre-sorted feedstock composed of at least 10 percent from municipal or commercial organic waste. Many of these facilities co-digest with animal wastes and municipal wastewater sludges. In Spain, 13 large capacity plants, averaging 70,000 TPY, are projected to be anaerobically treating nearly 7 percent or Spain's biodegradable MSW by the end of 2004. For all of Europe, the installed capacity has grown from 1.1 million TPY in 2000 and is projected to be 2.8 million TPY in 2004, an increase of more than 250 percent in four years. Figure ES-9 shows development of installed capacity of MSW AD facilities in Europe between 1990 and 2004. The annual capacity growth rate is above 20 percent. Single-stage anaerobic digesters account for approximately 92 percent of this installed AD capacity.

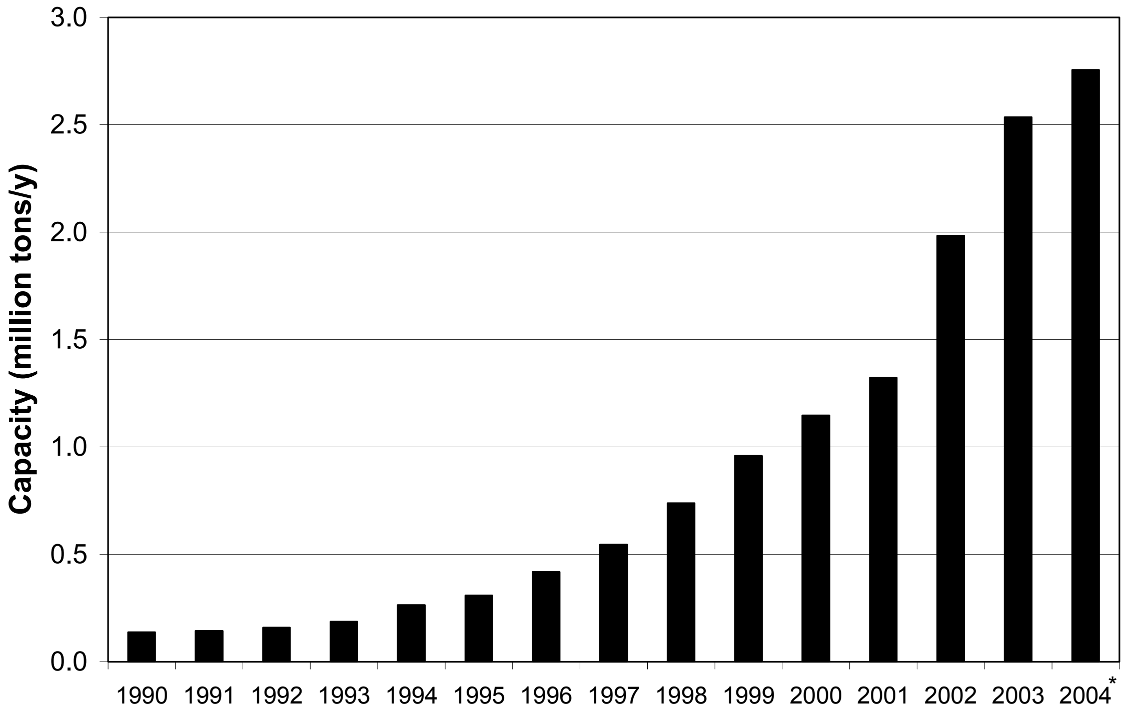

Fig. ES - 9: Growth Solid Waste Anaerobic Digester Capacity in Europe.
Adapted from L. DeBaere (2003)
***Data were projected for 2004**

Fermentation of biomass into ethanol is fully commercial for sugar and starch based feedstocks. It is not yet commercial for cellulosic biomass because of technical difficulties and cost, but this remains an active area of research and development. However, there are several facilities that are being commissioned. The Masada OxyNol process is permitted and expected to begin construction soon in Middletown, NY. This facility is permitted for 230,000 TPY of MSW and 71,000 bone dry TPY of biosolids with an expected annual output of 8.5 million gallons of ethanol. A facility is also planned by Genahol Inc. in Grove City, OH. The facility will be designed for a 275,000 TPY capacity and will process cellulosic and other biomass components of MSW. The annual yield is expected to be ten million gallons of ethanol. Other examples of cellulosic biomass to ethanol commercialization attempts include Iogen in Canada, BCI in Louisiana, and Arkenol with a plant in Japan. Initially, feedstocks in these ventures are intended to be agricultural and wood based residues. Both BCI and Arkenol proposed commercial projects in California but have not yet completed successful technology demonstrations in the state.

With respect to California, other than one operating full-scale landfill bioreactor demonstration project, there are no existing MSW biochemical processing facilities using anaerobic digestion or fermentation methods in the State. This is due to relatively low landfill tipping fees, low wholesale prices of product energy (methane or electricity), general lack of source-separation at the waste generation site, and lack of restrictions on landfilling of biodegradable material. There are several in-vessel digester projects proposed including a commercial scale facility for California State University – Channel Islands and a demonstration pilot scale facility at the University of California, Davis, both using a design developed at UC Davis. Recent announcements indicate that Los Angeles and the City of Lancaster are investigating anaerobic digestion projects with Bioconverter LLC. In at least two California jurisdictions that are investigating alternatives to landfilling, biochemical conversion is ranked either among the finalists or as the only qualifying process. A number of digestion projects are in development under state incentive programs for animal and food processing wastes.

Products of Thermochemical and Biochemical Conversion Processes

Thermochemical gasification processes are optimized to produce either fuel gases to be used in a mechanical or electrical power conversion process or synthesis gas to feed secondary chemical or fuel production processes.

The products of gasification and pyrolysis can be utilized in a range of secondary applications. A common application in many current installations is the combustion of the conditioned product gases to provide electricity or process heat. Advanced technologies employing combined cycles or fuel cells can generate electricity at higher efficiencies than simple steam-cycle mass burn systems. Gas storage prior to electrical conversion and the production of liquids both offer the capability to generate electricity on-peak as opposed to the base load operation of large mass-burn facilities. The value of the electricity is therefore substantially higher than for base loaded plants.

Storable gas, liquid, and solid fuels and chemicals can be produced by alternative techniques discussed here. The secondary processing of synthesis gas can be used to produce a range of liquid fuels and chemicals including methanol, dimethyl ether (DME), Fischer-Tropsch diesel fuel, hydrogen, synthetic ethanol, or substitute natural gas. For the production of these fuels or synthetic chemicals, the synthesis gases from gasification processes generally require less additional processing to produce valuable products than any other form of conversion technology other than the methane-rich biogas produced through anaerobic digestion. From an environmental perspective, the production of fuels and chemicals can provide environmental benefits in emissions reductions.

Products of biochemical processes include biogas, ethanol, and other alcohols for use as fuels or as chemical feedstocks. Biochemical processes can also be used to produce higher value chemical products. Biogas can also be upgraded to natural gas pipeline quality and compressed for use as a transportation fuel much like compressed natural gas (CNG). Ethanol is produced from a fermentation process and then distilled and dehydrated to yield fuel-grade ethanol. Ethanol can serve as an intermediate for hydrogen production, and may not require distillation with some autothermal catalytic reforming processes in research and development.

Digestate from digestion processes including lignin and other non-degraded components of the waste can be processed for fertilizer and soil conditioning applications. Alternatively, the material can be used in compost or dried and used as a boiler fuel for heat and power or converted to fuels through thermochemical means.

Environmental Impacts

Environmental implications of conversion technologies are critically important to the overall feasibility of these processes. While a number of studies have characterized emissions from individual alternative waste conversion processes, there is a lack of consistent comprehensive data for use in comparative analyses to make broad conclusions within and among technology classes. This is due to the wide variety of process configurations and control strategies that are uniquely applied to individual facilities and to the general immaturity of the technologies as applied to MSW. Most commercial facilities worldwide are evaluated on a case-by-case basis by regulatory agencies. There are, however, a number of facilities that provide emissions data from processes that employ similar pollution control strategies to those that would be used for alternative technologies in the state. Some of these data are useful in predicting potential environmental impacts of proposed facilities in California. In addition, there are alternative waste conversion sites under development in California. Direct measurements from these facilities are planned as these sites begin operation, providing for objective independent testing and verification of environmental performance.

Current information suggests that thermochemical and biochemical waste conversion processes can be operated in a manner that presents no greater threat to human health or the environment than current waste disposal practices such as mass burn incineration or landfilling. That being said, properly designed processes must adequately address air emissions, water quality, solid and liquid wastes, nuisance factors, and health and safety risk factors.

Air Emissions

While biochemical processes have gained widespread acceptance for treating various feedstocks, thermochemical processes have met with resistance from the environmental community and the public. Some of this resistance has stemmed from the misperception that pyrolysis and gasification processes are only minor variations of incineration or "mass burn." An essential difference between combustion (incineration), pyrolysis, and gasification is that the latter two are intermediate processes for producing gaseous, liquid, and solid products that can be used in a wide variety of applications. For the broader category of coal and petroleum gasification, the production of chemicals, fuels, and synthetic gases is actually more prevalent than electricity production. Pyrolysis processes can be optimized for the production of oils. In the case of chemical and fuel production, the emissions from a direct process effluent can be avoided, although consideration must be given to emissions from the ultimate use of these products as they are used or combusted downstream. Nevertheless, these downstream-use emissions would tend to be more dispersed rather than concentrated at a single site location, and might displace emissions from other sources, such as natural gas combustion, petroleum refining, and motor vehicle use of gasoline or diesel.

Although chemical and fuel production from gasification and pyrolysis of MSW components is possible, the most prevalent process is the use of producer gases for on-site electricity production. These post-combustion processes associated with alternative thermochemical conversion processes still differ dramatically from incineration in several key respects:

- Pyrolysis and gasification processes use lower amounts of air/oxygen or none at all.
- The volume of output gases from a pyrolysis reactor or gasifier is much smaller per ton of feedstock processed than that from an incineration process. While these output gases may be eventually combusted, the alternative processes provide an intermediate step where gas cleanup can occur. Mass burn incineration is limited in application of air pollution control equipment to the fully combusted exhaust only.
- Output gases from pyrolysis reactors or gasifiers are typically in a reducing environment, and can be treated with different technologies compared with a fully combusted (oxidative) exhaust. Reactant media can also be hydrogen or steam.
- Subsequent combustion of low molecular weight fuel gases from pyrolysis and gasification processes can be much cleaner than combustion of raw feedstocks .

These factors make control of air emissions less costly and less complex than that required for incineration.

While exhaust gas cleanup of non-combustion thermochemical conversion processes may be easier than that associated with incineration, proper design of the process and emissions control systems is necessary to ensure that health and safety requirements are met. The output products of pyrolysis and gasification reactors can contain a variety of potential process and air pollutants that must be controlled prior to discharge into the ambient air. These include particulate matter (PM), aerosols or tars, oxides of nitrogen (NO_x), oxides of sulfur (SO_x), dioxins and furans, hydrocarbon (HC) gases, multiple metals, and carbon monoxide (CO). There are many strategies for controlling emissions from thermochemical conversion processes, and they are highly dependent on the process requirements of each individual facility.

Contaminant removal from the exhaust stream is typically accomplished with a variety of technologies described in Table ES-2. These are often used in combination. As noted above, thermochemical conversion processes may employ air pollution control at the reactor outlet as well as the exhaust gas outlet.

Table ES-2 – Air Pollution Control Technologies

Contaminant	Control Technology
Particulate Matter (PM) and Aerosols	Inertial Separation, Baghouse, Scrubbers, Electrostatic Precipitators (ESP)
Volatile Metals (vapor state)	Carbon Filters (or condense to PM or aerosols and use PM separation techniques)
Dioxin/Furans	Limit chlorine mass input in feedstock, Cold-quenching and/or Catalytic/thermal Combustion
Carbon Monoxide (CO) and Hydrocarbon (HC) gases	Process Design, Catalytic/thermal Combustion, Re-burning, Carbon Filters
Oxides of Nitrogen (NOx)	Flame Temperature Control/ Low NOx Combustors, Fuel Nitrogen Management, Selective Catalytic Reduction, Water Injection, Re-burning
Oxides of Sulfur (SOx)	Limit sulfur mass input. Scrubber
Acid Gases	Scrubber

Emissions of dioxins and furans are an important environmental consideration. Dioxins and furans are compounds consisting of benzene rings, oxygen, and chlorine that are considered or known to be toxic or hazardous. Dioxins and furans can form when waste streams containing chlorine are processed under conditions where the flue gas has a significant residence time in a temperature range between 480 and 1290° F, with a maximum formation rate at approximately 600° F. They are typically formed downstream of the combustion process and frequently within the air emission control equipment. In this temperature range, hydrogen chloride (HCl) in the flue gas reacts with oxygen to form chlorine (usually catalyzed by heavy metal vapor, such as copper) and the chlorine subsequently reacts with hydrocarbon radicals to form dioxins and furans. The low levels of oxygen present in pyrolysis and gasification processes inhibits the formation of dioxins and furans (however HCl in product gas must be managed if combustion for heat or power follows gasification). Chlorine is an essential element in the formation of dioxins and furans, but studies of the impact of chlorine concentration in the feedstock on their formation give mixed results. For studies that have shown correlations between chlorine and dioxin and furan formation, a strong correlation is typically only observed at levels above 1-2 percent in the feedstock.

Some studies have shown the formation of dioxins and furans during pyrolysis of feedstocks containing chlorine, with most the dioxins and furans found in the product oils. Other studies have shown that removal of HCl in the flue gas using scrubbing techniques can reduce dioxins and furans to acceptably low levels, even for feedstocks containing up to 8 wt. percent chlorine. Alternatively or in addition to scrubbing, high-temperature combustion of intermediate gases can prevent de novo formation and destroy dioxins and furans already present. High-temperature combustion is, in fact, the recommended treatment for landfill gas collection systems. Aside from air pollution control measures, the amounts of chlorine and copper in the feedstock can also be limited to minimize potential formation.

Solid Residues

Heavy metals present in feedstocks are concentrated in ash or residual solids produced by virtually all conversion technologies. With proper management, the concentrated heavy metals can more readily be treated and disposed of in a controlled manner that poses lower environmental threat. In some cases, metals may even be recycled from the char/ash. In some processes, the ash is vitrified to form a slag. The slag is a hard, glassy substance that is formed when the gasification systems operate above the fusion or melting temperature of the ash. Since the non-volatile metals are fused into the slag, leaching of metals is reduced or eliminated. When demonstrated to be safe and metals sufficiently stabilized, the bottom ash and slag could be used in different construction and other applications.

Solid residues, mostly as cakes or powders of fine particulate matter, are generated by baghouse filters and electrostatic precipitators (ESPs) that are periodically cleaned. Bottom ash is also produced in some cases. For example, fluidized bed reactors may rely on sand and other inorganic material present in the fuel as make-up for the bed media lost through attrition (and mostly captured in the PM control system). Some of this material is periodically discharged to maintain proper bed level in the reactor. The discharged material may be useful as road aggregate, agricultural soil additive, or may be landfilled.

Significant quantities of solids remain following biochemical processing of MSW. This includes virtually all the lignin and some non-degraded cellulose or other carbohydrates. Much of this can be processed for fertilizer and soil conditioning applications, especially following aerobic composting, or used as a boiler fuel for heat and power or converted to fuels via thermochemical means.

Liquid Residues

Liquid wastes generated by alternative waste conversion processes include pyrolysis oils, spent acid solutions from acid hydrolysis in biochemical systems, boiler blowdown in thermochemical processes employing boilers, and spent scrubber solutions from air pollution control equipment. There are well-defined mechanisms already in place for dealing with spent acids and scrubber solutions although treatment costs can be high. Gas cleaning systems for gasification and pyrolysis in some designs also produce waste water or waste liquid streams that may contain tars, oils, chars, ash, and other constituents removed from the raw process stream. Pyrolysis oils are composed of a range of hydrocarbon compounds. Although some of these compounds can be toxic, they are also compounds commonly used in other industrial processes and may be recoverable in some form as commercial products.

Nuisance Factors

The nuisance factors associated with alternative waste conversion technologies can include noise, odors, fugitive emissions, dust, litter and debris, increased local traffic, aesthetics, and vectors. In general these impacts would not be expected to increase and may be reduced compared with what is experienced in existing solid waste facilities. The use of engines, turbines, and generators to produce electricity may result in increased noise, but this is commonly mitigated by enclosing the generating equipment in sound isolating enclosures. Conversion processes generally occur in an enclosed vessel so that odors, fugitive dust, and litter are not typically associated with the reactor component of the system. Co-location of conversion facilities at existing solid waste facilities will not result in any increased traffic because the existing transportation infrastructure can be used and material can be transported via conveyor belts. Traffic impacts may exist due to offsite transportation of commercial products and byproducts for marketing and disposal.

Other Risks

Other risks associated with conversion technologies may include potential acid or other chemical spills and leaks or breaches in high-pressure lines and reactors. These risks should be adequately managed by proper design and accommodated within other well-defined risk abatement mechanisms already in place for industrial processes. As with any new technology implementation, there may remain unforeseen risks until adequate experience is obtained.

Environmental Conclusions

From an environmental perspective, advanced alternative waste conversion technologies have several potential benefits over mass incineration or other current practices. Existing data and facilities indicate that conversion technologies can operate within existing regulatory constraints. Facilities with the most advanced environmental controls would very likely be able to meet regulatory requirements in California. The actual impacts of specific facilities will need to be evaluated on a case-by-case basis as part of a local permitting process.

Socio-Economic Impacts of Conversion Processes

As a resource, the organic portion of the MSW materials being buried in California landfills each year represents an estimated chemical energy equivalent to more than 60 million barrels of crude oil, sufficient to generate 2370 MW of base load electrical power. At a market price of over $37 per barrel, this energy resource could be considered to be worth more than $2 billion. For thermochemical processing, plastics are a particularly attractive component of the landfilled MSW stream, since they represent over 30 percent of the chemical energy in California MSW and are growing at almost twice the rate of biogenic organic materials.

The broad implementation of conversion technologies could affect the state economy in a number of different ways, including the introduction of new sources of products and energy, the diversification of product markets, extension of landfill lifetimes, increased recycling, decreased environmental impacts, job creation, and the specific economic impacts related to the plant itself.

Because California landfills a large amount of material that could be used as energy and material process feedstocks, significant positive economic impacts are possible. The application of conversion technologies to the waste stream could provide up to 8 percent of the state's current electricity consumption and help in achieving the goal of 20 percent renewable energy by 2017 required under the California Renewables Portfolio Standard Program (RPS).[†] Other significant product streams could include a wide range of liquid fuels and chemicals. The introduction of new production facilities could also provide a beneficial diversity of markets. This could reduce the state's dependence on imported petroleum resources or out-of-state electrical resources and ethanol.

Another potential societal benefit could be the extension of landfill space by directly diverting materials from the landfill. This could reduce the burden and need to permit new landfills and could facilitate improvements in land use practices.

In general, the use of conversion technologies around the world is fairly limited, although they are beginning to be implemented more widely in Japan and Europe. Energy markets and waste management policies in Europe and Japan combine to create conditions for commercializing combustion and non-combustion solid waste conversion systems. The economics for individual facilities in California will be site specific as the primary economic competition is the standard landfill. Most, if not all, systems reviewed rely on tipping fees to be economically viable. As such, a decrease in tipping fee rates, which could result from direct competition with landfills for material, would likely cause financial stress or failure of the project. Future measures that increase diversion of generated waste or place restrictions on the content of landfilled waste (an example would be to limit or ban biodegradable waste components or restrict average total organic carbon content) will help provide incentives for further diversion and waste reduction as well as implementation of conversion technologies. Several jurisdictions in California are conducting evaluations of landfill alternatives including the cities of Alameda, Los Angeles, and Hanford, and Santa Barbara County, Los Angeles County, and the Coachella Valley Association of Governments.

The impact from extensive adoption of conversion technologies is of great concern to the existing recycling and composting markets, landfill industry, waste reduction advocates, and landfill gas-to-energy producers. With the development of conversion technologies that can process a broad range of waste, some of the difficult to recycle materials may find a market in conversion. On the other hand, wider use of conversion technologies would likely result in greater effort in processing or sorting waste streams that are currently being sent directly to landfills. These offsetting factors were evaluated as part of a market study being conducted in conjunction with the life cycle analysis (LCA) project. The marketing study estimates that recycling rates for paper

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[†] Electrical potential from the renewable (biogenic) portion of the stream is equivalent to about 50% of the current amount of renewable electricity used in the State from all sources. To the extent that plastics made from petroleum or tires are used in conversion to energy, that portion of the energy produced would not be considered renewable.

would be unchanged by conversion technology implementation, metal and glass recycling rates would increase for both biochemical and thermochemical processes, and the plastic recycling rates would increase only for biochemical processes. On balance, conversion technologies are expected to augment recycling and composting activities, but some individual facilities may compete with traditional recycling and composting for feedstocks. However, it should be recognized that conversion technologies designed to produce fuels or other chemical based products such as ethylene from waste plastics or other materials represent another pathway for material recycling and can displace petroleum and other fossil feedstocks. The efficacy or efficiency of this type of material recycling should be compared to conventional recycling using an equal outcome basis.

Conclusions

On the basis of the information evaluated in this report, thermochemical and biochemical conversion technologies represent technically viable options for the conversion of post recycled MSW. Thermochemical and biochemical technologies are processes with unique characteristics that have different applications in reducing landfill volume. In some cases, combinations of these technologies are likely to be used in addressing post-recycled MSW (i.e., ecoparks).

Thermochemical conversion technologies, such as gasification and pyrolysis, can treat nearly all of the organic fraction of MSW and can, in general, treat a more heterogeneous feedstock, including high energy content plastics. Pyrolysis and gasification applications for MSW have expanded considerably in the past five years, especially in Japan that has limited domestic resources and limited landfill space. Over 50 commercially active facilities were identified with a total capacity representing approximately 8 percent of the current landfill stream in California. Of the two methods, gasification is more technologically complex but offers the capability of producing a broader array of products without additional upgrading.

The use of alternative biochemical technologies for processing fractions of the MSW stream has also increased significantly during the past five years. This includes processes such as anaerobic digestion and fermentation. Biochemical technologies are more limited in their application since they can only process biodegradable feedstocks. Most of the growth in biochemical technologies has been in Europe and is due to a combination of high tipping fees, restrictions on landfilling untreated waste, and high prices for renewable energy products. Currently, the European capacity of anaerobic digestion for MSW components represents approximately 7 percent of the current landfill stream in California. Biochemical technologies could also be used in combination with alternative thermochemical or other processes to provide broader reduction of landfilled material.

Feedstock selection and processing will depend on the specific requirements of each conversion technology being used as well as other local economic considerations. It is anticipated that conversion processes will use more up-front sorting processes to remove inorganic metals, and other potentially recyclable materials such as paper and some plastics. Additional sorting would likely be required for biochemical process to provide an input stream that is composed of essentially biodegradeable products. This would exclude the majority of the plastic and textiles, although these materials can be accepted, but are not transformed, in some biochemical processes. For thermochemical processes, materials that would contribute to toxic or other air pollutants could also be removed, if necessary. This could include feedstocks with high Cl content such as PVC or other feedstocks with significant quantities of volatile metals such as batteries. Air pollution controls will be needed in addition to the preliminary sorting so that a complete clean sort would not likely be required.

Conversion technologies provide the potential of converting materials that are currently landfilled into electricity, chemical, or other products such as synthetic diesel and gasoline transportation fuels, or precursors of petrochemical feedstocks such as ethylene, hydrogen, substitute natural gas and others.

Existing data and facilities in locations around the world indicate that conversion technologies can operate within constraints established by regulatory requirements. There has also been considerable technological progress in emissions controls over the past decade that can be directly applied to conversion technologies. These factors indicate that it is very likely that conversion technologies with the most advanced environmental controls would be able to meet regulatory requirements in California. The environmental risk of conversion technology facilities appears to be comparable with other common industrial practices provided the facilities are properly designed. However, the actual impacts of specific facilities will need to be evaluated on a "case-by case" basis as part of the local permitting process.

The viability of any single facility will depend on a number of factors including economic considerations, facility capital costs, and feedstock requirements and availability. While facilities are becoming operational throughout the world, the technological and economic risk will be facility-dependent. Given the heterogeneous nature of MSW feedstocks and the volatility of tipping fees and product prices, some risk remains with the use of conversion technologies. A number of facilities were identified that were unsuccessful for a variety of technical or economic reasons. Considering the potentially large market size and the rapid progress towards commercialization, however, conversion technologies appear to be well on their way to technological maturity with good efficiency, reliability, and environmental performance.

Recommendations

The following are recommendations related to the area of conversion technologies.

- It is suggested that the definition provided in AB 2770 for gasification be revised to provide a more scientifically correct description of the gasification process, if needed. An improved definition is contained in this report as follows:

  > "Gasification refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H_2, methane, and lighter hydrocarbons in association with CO_2 and N_2 depending on the process used."

- A more formal evaluation should be conducted of conversion technology vendors interested in marketing in California. This evaluation should include more specific information than can be obtained in a scoping study such as the present work. This information should include economic cost estimates, emissions data from third-party sources, and more specific detail on commercial status, including possible site visits for a limited number of already commercialized technologies. This evaluation should be conducted by a neutral, independent, third party.

- The State should investigate conversion technologies including, perhaps, sponsorship of a reasonable pilot scale demonstration facility within California which can be rigorously analyzed and operated with full public participation in order to develop verifiable and trusted operational data. A steering committee of stakeholders should be included at the outset.

- Improve the characterization of MSW. To predict the behavior of conversion systems and estimate type and quantity of emissions, detailed chemical composition and physical property data for feedstocks are necessary. Much information exists in the literature, but a review should be done to determine whether sufficient data exist for California waste streams. Where gaps are identified in the data, samples of California waste streams should be analyzed to fill these information gaps. The type of characterization by component and by gross sample includes:

    - Proximate, ultimate, and other elemental analysis including ash, metals, and toxic cogeners
    - Higher heating values (HHV)
    - Structural carbohydrate analyses (cellulose/hemicellulose/lignin) for cellulosic components
    - Protein/carbohydrate/fats for typical food and other wastes

  Recommendations could be made on the basis of these results as to which components should be pre-sorted from MSW being used for conversion.

- Additional data should be collected on emissions from thermochemical and biochemical conversion technologies. These emissions studies should be conducted by an independent third party and could include facilities at locations throughout the world, or most importantly in California as facilities become available. These emissions studies should include measurement of metals, dioxins and furans, other hazardous compounds, and fugitive gas and particulate matter emissions, in addition to criteria pollutants. The emissions results should be normalized to a standard use indicator such as volume or mass of material processed so that the values can be compared with other processes. These characterizations are typical of the type performed in life cycle assessment. Measurement of the composition of synthesis gas and other products prior to any combustion may also be useful in evaluating the system as a whole.

- Create co-funding methods to encourage the commercial development suitable for MSW conversion facilities. These could be co-located with existing landfills, material recovery facilities (MRFs), and other waste handling operations for maximum effectiveness in promoting reduction of mass flows into present landfills.

- Investigate issues and feasibilities of “complete stream recycling parks” (aka “ecoparks”) where current waste material enters the facility, is sorted and sent to processes that make best use of the material. Ideally, there would be no unvalued residues left for disposal.

1 Introduction

Landmark California legislation passed in 1989 (AB 939) established a solid waste diversion level of 50 percent by 2000. As a result, diversion efforts and measurements have been implemented in each jurisdiction in the state. From a recent estimate,[1] California diverts from landfills approximately 47 percent (statewide average) of solid waste generated.[*] Despite increasing diversion of solid waste from California landfills, (and nearly meeting the 50 percent diversion goal) the disposal of solid waste continues to be an important issue for the state.

While landfills can meet California's current disposal needs, difficulties with siting new landfills and increasing population will lead to diminishing landfill capacity. Environmental issues related to landfills will constrain future landfill development. These issues include production of landfill gas emissions, odors, vermin, rupture[3] or subsidence of landfill areas,[4] and landfill leachate incursion into groundwater.

Of the nearly 40 million tons of solid waste disposed in the state annually, about 80 percent is organic material (paper, wood, plastics, garden and food wastes). In the past 10 years, the amount of organic material annually diverted from landfills has grown from about 2 million tons to approximately 8 million tons, and the number of facilities using or converting this waste fraction has grown from 10 composting facilities to 170 operations. This includes composting, mulching, alternative daily cover (ADC), solid biomass combustion facilities that burn or co-fire urban wood waste, and three dedicated mass burn facilities.[5]

The California Integrated Waste Management Board (CIWMB) recognizes that the existing market for organic material utilization is not sufficient to consume the state's production of organic waste. Furthermore, it has become evident that there are barriers to increased diversion of organic material that are not simply or wholly based on economics. Among these barriers are certain statutory/regulatory restraints and a lack of data on potential technologies and markets.[6] Recommendations for addressing the identified barriers included legislation (AB 2770), and the initiation of information gathering activities such as technology evaluations, life-cycle analysis, and market assessments.

1.1 Options for Reducing Flow to Landfills

In addition to increasing reuse and recycling by continuing efforts to improve markets for waste paper, compostable material, and other recyclable material (conventional diversion technologies), there are only two other means for reducing material flow to landfill:

- Decrease the amount of waste generated.
- Increase the amount of residual material that is converted to energy, fuels or other products (i.e., transformation or emerging "conversion technologies").

[*] CIWMB estimates that the state generates approximately 75.7 million TPY of MSW or roughly 4,250 pounds per person per year.

Waste Reduction

Waste reduction and prevention involves changing the way goods are produced, packaged and consumed. Reducing the amount of waste from consumer goods packaging and transportation is viewed as a waste reduction strategy that does not limit consumer choice and product availability. In the U.S., solid waste from packaging and containers accounts for 32% of all MSW generated and 28 % of that disposed.[7] Methods to reduce packaging material per unit of consumable product include modifying container designs to reduce the amount of material per container, increasing the use of larger or refillable containers, and minimizing the use of secondary packaging. Secondary packaging can consist of many kinds of materials and is often immediately discarded after purchase and first use of the product. This secondary packaging is sometimes necessary for safety, food preservation, or to maintain product integrity during transportation. Often, large amounts of secondary packaging are used to invoke branding and product differentiation attributes to the item. If this additional packaging used as a marketing device results in increased sales of the product, then the manufacturer has economic incentive to continue to produce the secondary material, for which the cost of disposal is borne by the solid waste disposal system (tax or rate payers).

Europe has taken steps to reduce the amount of waste packaging material. The European Council Directive 94/62/EC (15 December, 1994) on packaging and packaging waste[8] directs member states to take measures relating to package waste production. In 1991, Germany invoked a policy approach called Extended Producer Responsibility (EPR) [χ] with the implementation of the German Packaging Ordinance. The law requires manufacturers and distributors to take back and/or recycle secondary and container packaging. Each company can either put its own system in place to recover all packaging material it produced and used to sell products or it can pay a fee to the central recovery company, which has responsibility for providing infrastructure for collecting, sorting and recycling packaging materials for the whole country. The fee manufacturers pay to the recovery company is based on the amount and type of packaging material used to get a product to market and sell it. The fee is eventually passed on to the consumer, but there is now an economic incentive to the manufacturer to reduce this fee by reducing packaging. According to the German recovery company (Duales System Deutschland AG),[9] the average consumer pays US$2.25 per month in higher prices due to this package recovery fee. Since implementation, the use of packaging has declined from 212 to 183 pounds per year per capita. What is remarkable is that more than 90 % of the packaging material is now recovered and approximately 80 % of the recovered packaging is recycled or converted in energy facilities. Most of the other member countries of the European Union (EU) are implementing similar programs for reduction and recovery of packaging waste. Although these programs have had some success in Europe, these programs have faced more obstacles in the United States for a variety of reasons including lack of political support to do so and greater landfill access and capacity.

Increase Conversion

The amount of material currently being disposed in landfills can also be reduced by increasing the chemical conversion to other useful products. The material sent to landfills in California

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[χ] EPR policy is essentially a 'producer pays' approach. It shifts responsibility of the post-consumer phase of certain goods to the product manufacturer.

represents a substantial resource, and continuing to landfill large amounts of organic and other material with substantial chemical energy content, such as plastics and polymers, may not be in the best interest of the state or society as a whole. Presumably, current recycled material market prices are not high enough to pay for recovering more of the disposal stream. This leaves landfill disposal as the only option for this large potential resource because costs and associated regulation of conversion processes are prohibitive.

Only organic or carbonaceous (carbon containing) materials in MSW can be utilized for the production of electricity, fuels, or chemical feedstocks. Of the nearly 40 million tons landfilled in the state, some 27 million tons are of biological origin, 4.4 million tons are plastics and textiles (also organic but usually derived from petroleum), and the remaining 8 million tons are mineral and other inorganic material (glass, metal, non-wood construction or demolition waste). Although inorganic material does not have any significant chemical energy, most of these inorganic materials contain a certain amount of “embodied energy” by virtue of having been manufactured. Some of this embodied energy is saved when recycling or reusing these inorganic compounds. Table 1 describes the landfilled waste stream in California. The table also shows the primary chemical energy content represented by each component. Figure 1 presents graphically the fractions of the energetic components of the landfilled stream (displayed both by mass and energy bases). Note that while paper and cardboard account for about 30 % of the disposed stream by mass, the category contains nearly 45 % of the total stream primary chemical energy. Plastics weigh in at about 9 % of the disposed stream and more than 25 % of the MSW primary chemical energy, due to their significantly higher chemical energy content per unit mass when compared with biomass organic materials.

Table 1-1. California Annual Landfilled Waste Stream Characterization with Estimated Chemical Energy Content by Component[10]

	Landfilled[a,d] (million tons)	Fraction of Total[d] (% wt.)	Moisture[b] (%wb)	Landfilled (million tons, dry)	Ash / mineral matter (million tons)	HHV [b] (BTU/dry lb)	Potential Chemical Energy (PJ)[c]	Equivalent barrels of crude oil (millions)	Potential Chemical Energy: Fraction of total (%)	Potential Chemical Energy: (rank)
Paper/Cardboard	11.3	30.3	10	10.2	0.60	7650	164	27	44.2	1
Food	5.9	15.7	70	1.8	0.29	6000	22	4	6.0	5
Leaves and Grass	3.0	7.9	60	1.2	0.12	6450	16	3	4.4	7
Other Organics	2.6	6.9	4	2.5	0.26	3800	20	3	5.4	6
C&D Lumber	1.8	4.9	12	1.6	0.09	8300	28	5	7.5	4
Prunings, trimmings, branches and stumps	0.9	2.3	40	0.5	0.03	8175	9	1	2.5	9
Biomass Components of MSW Total	**25.5**	**68.0**		**17.8**	**1.4**		**261**	**42**	**70.0**	
All non-Film Plastic	1.9	5.0	0.2	1.9	0.04	9475	38	6	10.2	3
Film Plastic	1.5	3.9	0.2	1.5	0.04	19400	59	10	16.5	2
Textiles	0.8	2.1	10	0.7	0.06	8325	13	2	3.4	8
Non-Biomass Organic Components of MSW Total	**4.1**	**11.0**		**4.0**	**0.14**		**110**	**18**	**30.0**	
Other C&D	2.5	6.7		2.5	2.5	-				
Metal	2.3	6.1		2.3	2.3	-				
Other Mixed and Mineralized	2.0	5.3		2.0	2.0	-				
Glass	1.1	2.9		1.1	1.1	-				
Inorganic Components of MSW Total	**7.8**	**20.9**		**7.8**	**7.8**	**0**	**0**	**0**	**0**	
Totals (1999)[d]	**37.4**	**100**		**29.7**	**9.4**	**(ave.)**	**370**	**60**	**100**	
Estimate for 2003[d]	**39.8**			**31.6**	**10.0**	**5900**	**394**	**64**		

a) California waste stream composite data (http://www.ciwmb.ca.gov/WasteChar/Study1999/OverTabl.htm), Accessed 3 May, 2004
& California Solid Waste Generation and Diversion (http://www.ciwmb.ca.gov/lgcentral/Rates/Diversion/RateTable.htm) Accessed 3 May, 2004
b) Adapted from Tchobanalglous, G., Theisen, H. and Vigil, S.(1993),"Integrated Solid Waste Management", Chapter 4, McGraw-Hill, New York
& Themelis, N. J., Kim, Y. H., and Brady, M. H. (2002). "Energy recovery from New York City municipal solid wastes." Waste Management & Research, 20(3), 223-233
c)100 PJ/yr is equivalent to 3.2 GW of chemical energy used continuously throughout the year
d) The latest Waste characterization data publicly available is from 1999. Potential Energy in 2003 disposal was estimated using the 1999 characterization. CIWMB is currently conducting a new characterization of the disposed waste stream and can be used in the 2003 energy estimate when available.

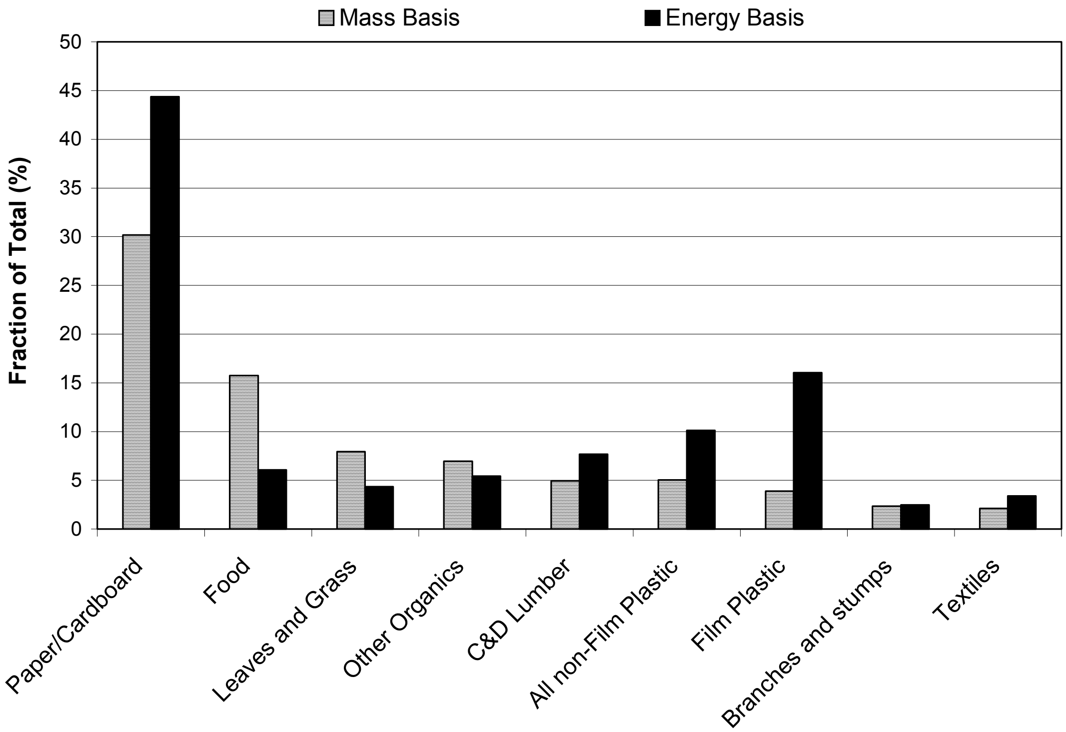

Fig. 1-1: Fractions of Total Mass and Energy of Waste Stream Components.[11]

Conversion Pathways

Conversion of carbon containing material can proceed along three main pathways;

- Thermochemical,
- Biochemical
- Physicochemical

All three pathways are utilized to varying degrees. This section lists the general definitions for the main processes (or technologies) that are covered by the three pathways mentioned above. In following sections, an overview of different technologies with detailed process descriptions is provided along with the current status of individual technologies in each area. Additionally, more detailed definitions are given for each major process area in order to further classify and differentiate among similar specific technologies.

A broad range of definitions currently exist for the different conversion methods. A more detailed discussion of the scope of definitions that can be found in the literature is provided in Appendix A. AB 2770 provided certain specific definitions of the terms "gasification," "solid waste facility," and "transformation." These definitions are discussed further below.

Certain discrepancies can be noted between the definition of gasification given in this report and the definition of gasification contained in AB 2770. The gasification definition contained in AB 2770 and Section 40117 of the Public Resources Code is overly restrictive and does not encompass the full range of technologies available for the conversion of MSW and other organic materials in California. The discrepancies raise two questions:

- 1) Should the definition of gasification now contained in the code be revised to permit its use beyond the production of electric power generation?
- 2) Are state objectives for environmental protection and waste management best met by defining specific allowable conversion technologies such as electric power generation, which may have higher environmental impact than those technologies than can produce synthetic fuels and chemicals, or instead by setting standards of performance for which any and all technologies are subject?

Regulating on the basis of narrowly defined conversion technologies rather than on environmental performance goals may tend to arbitrarily inhibit industrial innovation and unnecessarily constrain market development in this new area of enterprise. These are issues that the state should consider in moving forward with consistent and equitable waste management policies that could help establish new commercially viable chemical energy conversion industries for the reduction of waste materials going to landfill and the production of useful fuels and chemicals for the benefit of the state.

PRC Section 40117 defines gasification as follows:

> **40117.** "Gasification" means a technology that uses a noncombustion thermal process to convert solid waste to a clean burning fuel for the purpose of generating electricity, and that, at minimum, meets all of the following criteria:
> (a) The technology does not use air or oxygen in the conversion process, except ambient air to maintain temperature control.
> (b) The technology produces no discharges of air contaminants or emissions, including greenhouse gases, as defined in subdivision (g) of Section 42801.1 of the Health and Safety Code.
> (c) The technology produces no discharges to surface or ground waters of the state.
> (d) The technology produces no hazardous waste.
> (e) To the maximum extent feasible, the technology removes all recyclable materials and marketable green waste compostable materials from the solid waste stream prior to the conversion process and the owner or operator of the facility certifies that those materials will be recycled or composted.
> (f) The facility where the technology is used is in compliance with all applicable laws, regulations, and ordinances.
> (g) The facility certifies to the board that any local agency sending solid waste to the facility is in compliance with this division and has reduced, recycled, or composted solid waste to the maximum extent feasible, and the board makes a finding that the local agency has diverted at least 30 percent of all solid waste through source reduction, recycling, and composting.

Under this definition, processes that gasify waste to produce clean burning fuels or chemicals for uses other than in electricity generation would not be considered gasification and would still be considered transformation. The gasification process provides not only fuels for generating electricity, but also fuels or chemicals for virtually any application including transportation fuels, agricultural chemicals, synthetic fibers, plastics and polymers, heating, process steam raising, and other uses. Gasification processes can thus provide feedstocks for the synthesis of valuable chemicals and other products and reduce the state's reliance on imported petroleum, coal, and natural gas primary energy resources.

Many gasification processes use oxygen or air internally as a reactant to generate the heat necessary for the pyrolysis and gasification to occur. The heat can also be provided by indirect means or by heat releasing reactions using compounds other than oxygen. Direct gasification processes would appear to fail to satisfy part (a) of the definition, for example, even though they might meet all other parts of the definition as well as or better than some other qualifying gasification processes. Additionally, it is unclear why ambient air is allowed by part (a), but heated air is not (heating the input oxidant stream from waste heat elsewhere in the process is a common method used to improve overall energy conversion efficiency).

The definition does not guarantee superior environmental performance. For this and other reasons discussed, an alternative definition for gasification is used here to represent the range of processes and technologies associated with gasification.

Thermochemical Conversion Pathways

Thermochemical conversion is characterized by higher temperatures and conversion rates than most other processes. Thermochemical conversion includes a continuum of processes ranging from thermal decomposition in a primarily non-reactive environment, (commonly called pyrolysis) to decomposition in a chemically reactive environment (usually called gasification if the products are primarily fuel gases or complete combustion if the products are fully oxidized). Pyrolysis can be considered an incomplete gasification process, in which a mixture of gaseous, liquid and solid products are produced, each of which may have some immediate use to sustain the process. The characteristics of each of these different processes can also vary depending on the oxidizing or reducing media, process temperature and process pressure.[*][12]

Combustion Definition

Combustion is the complete oxidation of the fuel for the production of heat at elevated temperatures without generating commercially useful intermediate fuel gases, liquids, or solids. Combustion of MSW or other secondary materials is generally referred to as incineration. Flame temperatures range typically between 1500 and 3000º F depending on fuel, oxidant, stoichiometry, furnace design, and system heat loss. Particle temperatures in heterogeneous (e.g. unsteady reactions between solid and gas phases) combustion can differ from the surrounding gas temperatures, depending on radiation heat transfer conditions. Combustion of solids involves the simultaneous processes of heat and mass transport, progressive pyrolysis, gasification, ignition, and burning, with no intermediate steps and with an unsteady, sometimes turbulent, fluid flow. Normally, combustion employs an excess of oxidizer to ensure maximum fuel conversion, but it can also occur under fuel-rich conditions. Products of combustion processes include heat, oxidized species (e.g. carbon dioxide [CO_2], water [H_2O]), products of incomplete combustion and other reaction products (mostly as pollutants), and ash. Other processes, such as supercritical water oxidation and electrochemical oxidation can produce similar end products at lower temperatures but higher pressures.

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[*] Supercritical water oxidation and gasification are examples of chemical conversion methods that use very high pressure.

Gasification Definition

Gasification typically refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H_2, methane, and lighter hydrocarbons in association with CO_2 and N_2 depending on the process used. Alternative configurations using either indirect heating methods such as externally fired burners or autothermal methods using exothermic reducing reactions have been demonstrated. While gasification processes vary considerably, typically gasifiers operate from 1300^{o}F and higher and from atmospheric pressure to five atmospheres or higher. The process is generally optimized to produce fuel or feedstock gases. Gasification processes also produce a solid residue as a char, ash, or slag. The product fuel gases, including hydrogen, can be used in internal and external combustion engines, fuel cells, and other prime movers for heat and mechanical or electrical power. Gasification products can be used to produce methanol, Fischer-Tropsch (FT) liquids, and other fuel liquids and chemicals, (see Chapter 4). Gasification of solids with subsequent combustion of the gasification-derived fuel gases generates the same categories of products as direct combustion of solids, but pollution control and conversion efficiencies may be improved. Alternatively, the produced synthesis gases can be used directly for liquid fuel or chemical synthesis, eliminating or delaying the combustion process and the emission of resulting effluent.

Pyrolysis Definition

Pyrolysis is a process similar to gasification except often optimized for the production of fuel liquids (pyrolysis oils) that can be used straight (e.g. as boiler fuel) or refined for higher quality uses such as engine fuels, chemicals, adhesives, and other products. Pyrolysis also produces fuel gases, and the solid residue contains most of the inorganic portion of the feedstock as well as large amounts of solid carbon or char.

Usually, a process that thermochemically degrades material without the addition of any air or oxygen is considered pyrolysis. Pyrolysis typically occurs at temperatures in the range of 750-1500^{o} F. Pyrolysis and combustion of pyrolysis-derived fuel liquids and gases also produce the same categories of end products as direct combustion of solids. Like gasification, their pollution control and conversion efficiencies may be improved. Where fuel liquids are produced, the eventual site of emission of combustion products may be considerably displaced from the source of fuel production (e.g., vehicle emissions).

Plasma arc and radio frequency (or microwave) heating refer to specific devices providing heat from electricity for gasification, pyrolysis, or combustion depending on the amount of reactive oxygen, hydrogen, steam, or other reactant fed to the reactor. Plasma arc processes use electricity passing through electrodes to produce a discharge converting the surrounding gas to an ionized gas or plasma. Gases heated in plasmas typically reach temperatures of 7000^{o} F and higher.

Catalytic cracking is a thermochemical process that employs catalysts using hydrogen-driven reducing reactions to accelerate the breakdown of high molecular weight compounds (e.g., plastics) into smaller products for the purposes of improving selectivity and imparting certain desirable characteristics to the final product, such as volatility and flashpoint of liquid fuels. This cracking process is often employed in oil refinery operations to produce lower molecular weight hydrocarbon fuels such as gasoline from heavier oils, distillation residuals and waste plastic.

Biochemical Conversion Pathways

Biochemical conversion proceeds at lower temperatures and lower reaction rates and can offer high selectivity for products. Higher moisture feedstocks are generally good candidates for biochemical processes. Non-biodegradable organic feedstocks, such as most existing plastics, are not convertible by biochemical processes.

Anaerobic Digestion Definition

Anaerobic digestion is a bacterial fermentation process that is sometimes employed in wastewater treatment for sludge degradation and stabilization. This is also the principal process occurring in the decomposition of food wastes and other biomass in landfills. Anaerobic digestion operates without free oxygen and results in a fuel gas called biogas containing mostly CH_4 and CO_2 but frequently carrying other substances such as moisture, hydrogen sulfide (H_2S), and particulate matter that are generally removed prior to use of the biogas. Anaerobic digestion is known to occur over a wide temperature range from 50 to 160º F. Anaerobic digestion is also being explored as a route for direct conversion to hydrogen. Anaerobic digestion requires attention to the nutritional needs and the maintenance of reasonable temperatures for the facultative and methanogenic bacteria degrading the waste substrates. The carbon/nitrogen (C/N) ratio of the feedstock is especially important. Biogas can be used after appropriate gas clean up as a fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, and the manufacturing of chemicals.

Aerobic Processing Definition

Aerobic conversion includes most commercial composting and activated sludge wastewater treatment processes. Aerobic conversion uses air or oxygen to support the metabolism of the aerobic microorganisms degrading the substrate. Nutritional considerations are also important to the proper functioning of aerobic processes. Aerobic processes operate at much higher reaction rates than anaerobic processes and produce more cell mass, but generally do not produce useful fuel gases. Aerobic decomposition can occur from as low as near freezing to about 160 ºF.

Fermentation Definition

Fermentation is generally used industrially to convert substrates such as glucose to ethanol for use in beverage, fuel, and chemical applications and to other chemicals (e.g., lactic acid used in producing renewable plastics) and products (e.g., enzymes for detergents). Strictly speaking, fermentation is an enzymatically controlled anaerobic process although the term is sometimes more loosely applied to include aerobic processing as well.

Fermentation feedstocks require pretreatment by chemical, physical, or biological means to open up the structure of biomass and reduce the complex carbohydrates to simple sugars. This set of pretreatments is often referred to as hydrolysis. The resulting sugars can then be fermented by the yeast and bacteria employed in the process. Feedstocks high in starch and sugar are most easily hydrolyzed. Cellulosic feedstocks, including the major fraction of organics in MSW, are more difficult to hydrolyze, requiring more extensive pretreatment.

Ethanol and carbon dioxide are the primary products of glucose fermentation by yeast. Ethanol inhibits microbial growth and fermentation, often essentially halting the fermentation when the ethanol concentration reaches about 12 percent. Ethanol must be removed from the fermentation broth to be used as fuel.

Processes are also in development that would convert ethanol to hydrogen without distillation. Although ethanol fermentation and anaerobic digestion are commonly classified separately, both are fermentation. Lignin in biomass is resistant to fermentation. Process residuals are typically considered for compost, boiler fuel, animal feed, or as a feedstock for thermochemical conversion to other fuels and products.

Physicochemical Conversion Pathways

Physicochemical conversion involves the synthesis of products using physical and chemical processing at near-ambient temperatures and pressures. It is primarily associated with the transformation of fresh or used vegetable oils, animal fats, greases, tallow, and other suitable feedstocks into useful liquid fuels and chemicals such as biodiesel, frequently by transesterification, a reaction of an organic glyceride with alcohol in the presence of catalyst.

1.2 MSW Combustion (commonly known as Incineration)

MSW and various fractions are currently burned in combustion facilities to recover energy (as well as for mass and volume reduction) in all parts of the world. It is estimated that over 130 million tons annually are converted to energy in over 600 facilities worldwide. There are more than 100 facilities in the U.S. currently burning MSW for energy recovery (about 2/3 of them on the East Coast).[13] In California, three operating power plants consume MSW as the primary fuel with a combined generating capacity of approximately 70 MW_e. There is one facility in Stanislaus County and two in the Los Angeles area.[†] The largest source of electricity from MSW in California currently is landfill gas to energy facilities. Currently, 51 landfills in the state are recovering landfill gas for use as energy (LFGTE) with a combined generating capacity of 210 MW_e.

Europe and Japan by far outrank North America in terms of numbers of installations that convert MSW (includes combustion and non-combustion thermochemical and biochemical MSW conversion facilities). Europe's efforts have been motivated by higher landfill costs related to less available land, and the producers' responsibility to recycle or reuse product waste. More recently, strong incentives for landfill alternatives have evolved from upcoming restrictive landfill diversion requirements, in combination with Kyoto Protocol greenhouse gas reduction goals. In Germany, for example, biogenic carbon and energy limits have been set on disposed material. Material going to landfill is restricted to a total biogenic organic carbon (TOC) of ≤18 %, and an energy content ≤ 2580 Btu/lb[14] (California's average disposed MSW stream has an energy content (HHV) of about 4675 Btu/lb as received or 5900 Btu/lb dry basis [Table 1-1]). Enough of the biodegradable carbon containing and energetic components of the waste stream must be reused and recycled or undergo treatment that reduces the carbohydrate content (such as conversion to other products) in order to meet Germany's landfill requirements.

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† LACSD Refuse-To-Energy Facilities at Commerce
http://www.lacsd.org/swaste/Facilities/RTE/CommerceRTE.htm and Long Beach
http://www.lacsd.org/swaste/Facilities/RTE/SERRFOperation.htm

To reduce greenhouse gas emissions in attempts to comply with the Kyoto Protocol, the EU is implementing strategies that include increased use of energy produced from renewable sources. The European Community Directive 2001/77/EC (27 September 2001) contains definitions for renewable electrical energy sources. Biomass is, of course, a renewable source. The EC Directive includes in the definition of biomass- "the biodegradable fraction of industrial and municipal waste"[15] (although this definition appears overly restrictive depending in turn on a definition of "biodegradable" that may discount some fraction of biomass). The Directive also advises that of the electricity produced by facilities that consume both renewable and non-renewable organic feedstocks, only that portion attributable to the renewable energy source is considered renewable electricity.[16] Electricity and heat from the organic portion of MSW is considered renewable in the Netherlands[17] and Switzerland. That fraction in Switzerland is 50 %, based on a recent feedstock characterization for MSW combustion facilities.[18]

In Japan there are additional motives for improving upon alternatives to landfill. Japan's lack of significant domestic (traditional fossil) energy resources in combination with very limited space for landfills has led to the development of a large industry in solid waste combustion for energy. Approximately 75 % of the solid waste in Japan is converted in combustion facilities.[19] Environmental issues related to emissions from these waste combustion facilities and leaching problems from the generated ash have caused the Japanese government to investigate and invest in better air pollution control technologies and methods to stabilize the ash. The Japanese Environmental Agency estimates that dioxin emissions in 1998 were reduced by 70 % from 1997 levels, and legislation required 2002 emissions to be only 10 % of the 1997 levels. A range of processes have been developed through this effort in Japan including high-temperature gasification (oxygen blown or plasma arc) with ash melting and specific plasma arc systems for melting ash from MSW combustion facilities.

In the U.S., one of the primary issues preventing the expansion of MSW incineration facilities is that of air emissions. Chlorinated organic compounds emissions, especially polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F), have been linked to combustion of MSW. In the late 1980s, combustion of MSW was listed as the leading source of dioxin emissions in the country (approximately 60 % of total). Maximum available control technology (MACT) regulations promulgated by the EPA in 1995 forced the industry to retrofit with better emission control technologies where possible and shut down facilities that could not be improved. Today, the level of dioxin air emissions from combustion of MSW in the U.S. has decreased from 8900 g toxic equivalent (TEQ) per year in 1987 to 12 g TEQ per year by 2000, a decrease of 99.9 %.[20] During this period, the number of operating facilities increased and the amount of waste burned doubled from 15 million to 32 million TPY. Dioxin emissions to the atmosphere from all sources have decreased by an order of magnitude from 14,000 g TEQ per year to 1100 g TEQ per year. Solid waste combustion is now responsible for only 1 % of U.S. dioxin air emissions. Figure 1-2 gives an inventory of dioxin air emissions in the U.S. by source type. The formation mechanisms and control of dioxins and furans is discussed in greater detail in Chapter 5.

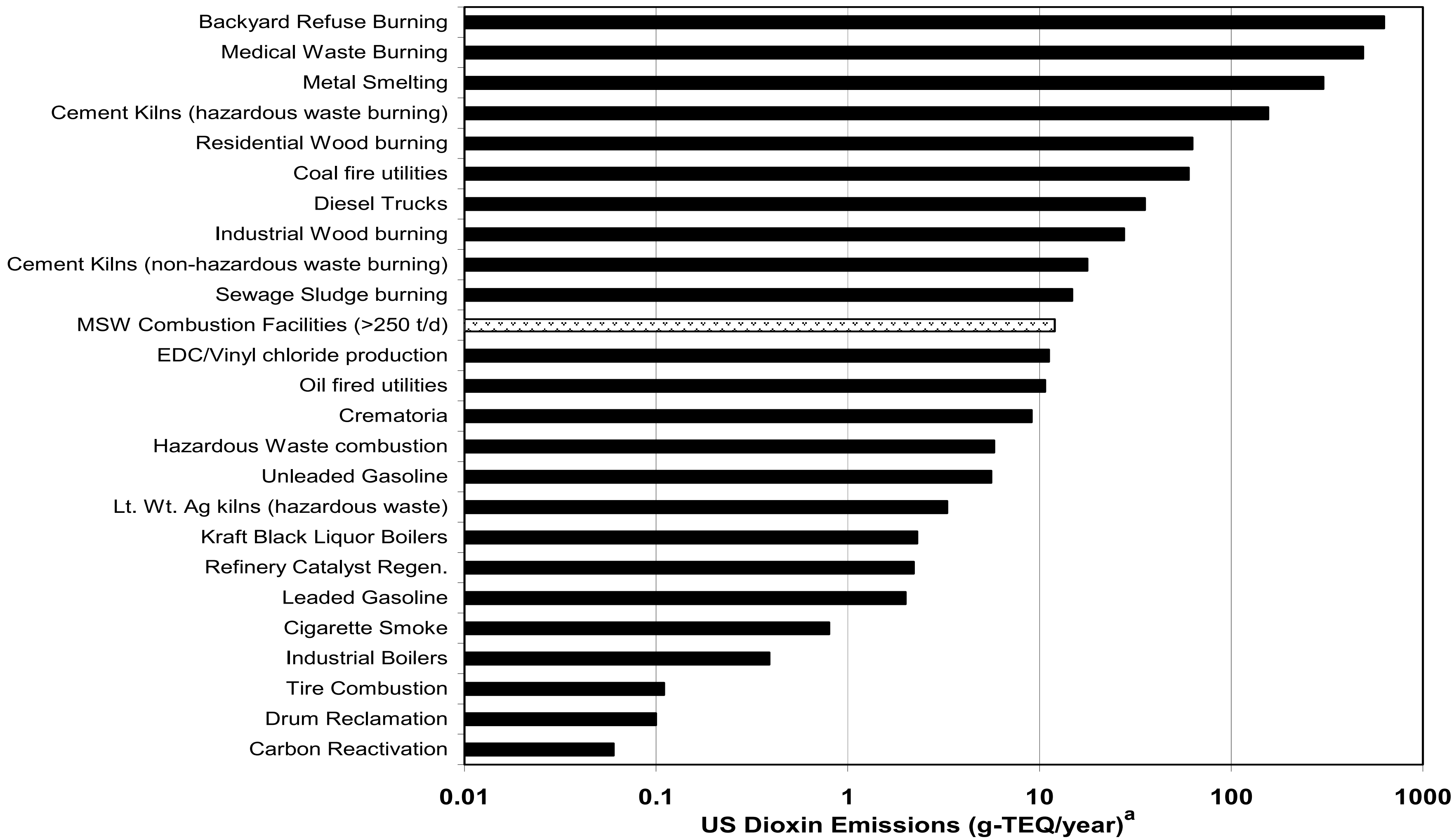

Fig. 1-2: US Dioxin Emissions Inventory by Source Type.
Data for MSW combustion is for 2000.(US EPA (2002) Docket A-90-45, VIII. B.11). All other emissions are from 1995 US EPA Inventory (http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=20797)

Though PCDD/F emissions have declined considerably due to improved combustion and air pollution control systems, the perception that unacceptable dioxin emissions are linked to solid waste combustion remains strong among a large portion of society. Opponents of burning solid waste have influence with policy and decision makers and the public so that siting new facilities can be difficult. In California, current law also discourages solid waste combustion by not allowing material sent to combustion facilities to be counted as diversion from landfill.*

1.3 Alternative Conversion Technologies

While combustion of MSW has undergone considerable scrutiny over the years, the need remains to reduce landfill volume. Other technologies that utilize thermochemical and biochemical processes may provide an additional viable option in the conversion of waste. Developing policies have yet to settle how much of post-sorted MSW when converted in non-combustion thermochemical conversion systems will be allowed to be counted as diverted waste, while allowing biochemical conversion of MSW to be counted completely as diversion. This type of regulation that favors one class of conversion technology while putting hurdles in front of another class, based on perceived advantages or disadvantages, rather than rigorous scientific analyses, may not be the best approach for protecting the environment and public health. By combining a detailed technical evaluation along with a rigorous life cycle analysis (LCA) of each conversion technology, for example, an objective basis for setting rational environmental emissions and performance standards can be obtained. LCA of various options is being conducted as part of a related study.[21]

AB 2770 directed the CIWMB to investigate and evaluate non-combustion conversion technologies suitable for post-recycled MSW. The goal of this investigation was to provide a better understanding of the potential for these technologies to address a portion of the landfill problem and to understand what environmental and other impacts these technologies would have if they were put into place. In this report, the results of an evaluation of alternative (non-combustion) MSW conversion technologies are documented and analyzed. These data (to be published in a separate, searchable database), were gathered for this evaluation from a variety of sources including information generated from a survey of the industry and development community worldwide (Appendix B contains a copy of the survey). A list of preliminary entities used for initial contact was generated from those components utilizing municipal waste contained in an earlier database on general (mainly biochemical) conversion technologies (of biomass) that was developed at UC Davis, in previous work.[22] This database is available on the Internet at

http://cbc1.engr.ucdavis.edu/conv/home.htm

and can be accessed and viewed interactively or downloaded as a Microsoft Excel® file. A listing of companies that provided information in the form of either a survey response or informational literature is provided in Appendix C.

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* Installation of new MSW combustion facilities is not prohibited if they meet all applicable emissions and permitting requirements. However, the disincentive is that the MSW consumed in combustion facilities will be considered disposal and not diversion for purposes of AB 939 accounting.

Primary attributes used in developing quantitative evaluation criteria for the technologies and systems are:

- Degree of reduction in material requiring landfill disposal.
- Emissions and environmental impact per unit of material converted.
- Chemical potential energy in waste stream converted to energy of added value.
- Ability to interface, and possibly enhance existing MSW/recycling infrastructure.

2 Feedstocks

2.1 Separation and Sorting

Generally, MSW will need various forms of pretreatment before conversion technologies can be effectively applied. In its simplest form, this pretreatment will involve sorting of the MSW (though some process suppliers claim that unsorted material is accepted as feedstock and useful materials ending up in the residue can be extracted at the back end). Existing sorting operations in the MSW flow path are usually concentrated at three points:

- Waste origination source, with selective sorting of the generated waste into dedicated collection barrels for green waste, recyclable materials and general garbage or trash.
- Material Recovery Facilities (MRF), with selective sorting of the as received "recyclable materials barrel," into separate streams for each recyclable material, inadvertent hazardous materials (such as batteries), and non-recyclable materials that will be sent to the landfill.
- Transfer Stations, where MSW is unloaded from collection vehicles and briefly held before it is reloaded on larger, long distance transport vehicles for shipment to landfills or other treatment or disposal facilities. Typically, only minimal sorting of items such as tires, batteries, etc. is done at this point.

From the analysis of the conversion technologies for MSW, it is proposed that enhanced transfer stations (ETS) be created that will allow additional sorting to select streams for disposal using conversion technology plants (ACTP) co-located adjacent to the ETS. Since the entire biomass and non-biomass organic material components of MSW were identified as the primary candidate materials for effective ACTP, the ETS would only have to develop technologies that separate inorganic materials (glass and metals) from the as-received MSW. Technologies for separating inorganics are relatively straightforward and widely applied in existing MRFs. Other technologies can be implemented to provide an addition level of removal for some of the biomass components that can be sent to composting facilities. The development of an appropriate separating technology is considered a critical enabling technology that allows ACTPs to operate efficiently and economically. Further work is needed to articulate the potentials of ETSs so that a template for state application can be developed if that is desirable.

Biochemical processes can convert the biodegradable portion of MSW. This includes paper/cardboard, green wastes, food wastes, and other biomass. Not all biodegradable components can be digested or fermented equally. Biochemical processes ideally would be fed only the portions of waste that are quickly and efficiently converted, but this usually requires source separation or costly and complex sorting facilities. Most practical digestion or fermentation systems can accept some amount of the biologically inert components of the waste stream (e.g., plastics, metals, glass, some woody material, and mineral matter), and they simply expel the inerts with the digestate. Existing conversion facilities in Europe submit the waste stream to extensive mechanical sorting and/or obtain source-separated feedstock.

Steam Sterilization

This technology, as has been demonstrated by Brightstar Environmental, subjects raw MSW to a process of pasteurization. Steam autoclaving is used to sterilize the MSW and permit relatively safe handling and sorting by human operators. After sterilization, the MSW can subsequently be screened to remove metals, glass, and plastics for separate recycling and/or re-use through the existing infrastructure. The remaining organic MSW could also potentially be channeled for transfer to an appropriate ACTP input feed. This technology goes beyond the more typical pretreating operations that focus primarily on sorting inorganics and other components using various other manual and automatic processes, and would likely add additional capital costs.

2.2 Feedstock Availability

Paper

Paper and cardboard material currently disposed in landfills comprise the largest category of biomass that could be utilized as a feedstock for conversion technologies. Paper represents about 30 % of the landfill waste by weight, or more than 12 million tons of material (see Table 1-1). Some of the larger classifications within this group include OCC (old corrugated containers), ONP (old newspapers), and mixed paper. Although recycling of OCC and ONP materials is a well developed industry in California, the overall paper/cardboard recycling rate is only slightly higher than 30 %, or approximately 4.5 million tons of material.[*] California relies heavily on foreign markets to consume its recovered paper (In 1997, California shipped about 36 % of its recovered post consumer paper to foreign markets, primarily China).[23] However, paper/cardboard contains over 44 % of all the chemical energy in MSW, so the value of this potential energy as a feedstock for conversion to alternative fuels is high. According to the American Forest and Paper Association (AFPA), in 2002 overall paper fiber recovery rate was 48 % for the United States.[24]

OCC represents approximately 4.6 % of the waste stream to landfills in California, or 1.8 million tons.[25] Recovery rates for OCC are about 70 % nationally,[26] well above the average for all paper. The latest recovery rates for OCC in California are 51.8 % for 1995.[27] The lower recovery rates for California are due in part to the fact that the AFPA includes preconsumer scrap, which represents an estimated 10.8 % of recovered OCC, in the national rates and that the AFPA assumes that equal amounts of new corrugated packaging are imported and exported. OCC is recovered primarily from larger businesses, and many large generators of OCC such as supermarkets and department stores already have OCC recovery programs in place. Most of the OCC is consumed by in-state paper recycling mills that rely on OCC as their primary feedstock. One of the main issues with OCC recovery is capturing the stream generated by small businesses. Compared with larger businesses, the economics of recovery is considerably poorer and space constraints restrict small business collection. Recovery rates for the residential sector, which represents approximately 10 % of the OCC generated, are also low, accounting for roughly 3 % of the recovered OCC.[40]

ONP represents approximately 4.3 % of the waste stream to landfills in California, or 1.7 million tons. ONP recovery rates are also higher than those for paper as a whole at approximately 60 % nationally.[28] ONP recovery rates for California in 1995 were similar at 58.7 %.[40] A majority of the ONP is generated in the residential sector, approximately 85 % by U.S. EPA estimates.[41] Interestingly, as of 1995, only 43 % of the ONP recovery came through curbside recovery programs, although other sources of residential sector recovery include recycling centers and paper drives of various sorts.[40] With smaller generation rates, the recovery of ONP from the commercial sector is considerably less economical.

[*] Last estimated by CIWMB to be 31% in 1997 <http://www.ciwmb.ca.gov/Paper/> (Dec.1, 2003).

Mixed paper represents a broader category of miscellaneous paper. One of the most significant barriers for the recovery of mixed paper is the low value of the commodity. Generally the value of mixed paper is lower than the cost of collecting and processing the material, although the economics can be positive if the avoided disposal costs are factored in.[29] Mixed paper is primarily recovered from residential sources, and represents approximately 20 % of all paper recovered in curbside programs in California. According the U.S. EPA estimates, however, mixed paper represented more than 40 % of the recycled paper generated in residences.

Plastics

The plastics component of the waste stream is an attractive feedstock for conversion. By weight, plastics compose approximately 9 % of the currently disposed waste stream or 3.6 million TPY in 2000 (see Table 1-1). Film plastic (1.6 million TPY) is the largest component (43.6 %) of the plastic waste stream, representing 3.9 % of the total waste. Since plastics have calorific values between 2 and 3 times those for biomass organics (mass basis, Table 1-1), plastics contain over 25 % of all the chemical energy in MSW materials. HDPE and PET make up 8.7 % and 5.1 % of the plastic waste, and 0.8 % and 0.5 % of the total landfilled waste, respectively. Durable plastic items and composite plastics make up 20 % and 15 % of the plastic waste, and 1.8 % and 1.3 %, respectively, of the waste stream.[30]

Plastic use and disposal is continuing to grow and this trend will likely continue in the foreseeable future. Nationally, plastics sales have grown at a rate of 4.9 % annually since 1973, with sales of more than 50 million tons in 2000. Plastics in the MSW stream increased from 0.5 % (390,000 TPY) in 1960 to 13.8 % (22.8 million TPY) in 1999.[31] Because of their comparatively low density, plastics represent an even larger volume of the landfilled material, which could be as much as twice the percentage on a weight basis. This increases the cost of landfilling plastic on a mass basis over higher density materials.

Recycling of plastic is generally considered to be higher in the waste processing hierarchy than conversion (disposal being at or near the bottom). As such, recycling of plastics (or any component of the waste stream) is favored over disposal. The recycling of plastics has been going on since the 1970s and has become an established industry for some plastics components. Two of the more successful plastics recycling industries are the PET and HDPE beverage containers, which account for more than one-half of the national plastics recycling industry.[32] PET plastics recycling increased dramatically in the early 1990s with a peak recycling rate of 71 % in 1994. In recent years, however, the number of new types of containers and different beverages such as bottled water has grown significantly, making it more difficult to recycle and resulting in a corresponding drop in recycling rates. From 1999 to 2001, for example, the number of PET beverage containers sold in the state more than tripled. Although the number of recycled PET bottles increased annually by approximately 300 million containers, PET recycling rates still dropped from 65 % in 1999 to 34 % and 36 %, respectively, in 2000 and 2001.[33] The other plastic type that enjoys significant recycling is HDPE, which is used in milk jugs and other bottles and tubes. The recycle rate of HDPE containers is still relatively low, however, with only 43,600 of the 348,400 available HDPE containers recycled in California in 2000, or approximately 13 %.[34]

The level of recycling for other types of plastics is typically small, around 5 % overall. Film plastics are recycled in a number of applications including composite lumber such as decking, siding and other products that use a mix of plastic and wood or sawdust. These markets have less stringent quality standards than for other film applications such as trash bags, and hence can be produced from a wider range of waste plastic materials. Film plastics for these applications are obtained from collection systems at grocery stores or other locations. More than 40 % of the film plastic disposed as waste statewide is from residential sources, but a great deal of it might not be suitable for recycling because of food contamination.[35]

One of the main problems with plastic recycling is that it tends to be uneconomical. Plastics are lightweight and can include multiple resin types and usually must be sorted before recycling.[†] Collection and processing costs typically exceed the value of the scrap material by more than 2 times.[36] As additional container types are introduced into the waste stream and more intensive sorting is required, recycling costs could increase further. The California Bottle Bill, which charges a deposit on beverage containers, can help to subsidize the cost of recycling plastic containers. For PET recycling, funds are utilized from unredeemed beverage deposits, with more limited assistance provided by plastic container manufacturers.

Because of their relative high chemical energy (approximately 25 % of the total chemical energy), plastics are attractive candidate materials for conversion technologies that either produce alternative fuels or chemicals, or fuel gases for power conversion to electricity. As conversion technologies develop to use a larger fraction of waste, composition of plastics and other materials may need to be modified with conversion in mind. For example, alternatives to PVC may find greater market acceptance as costs are imposed on chlorine in the feedstock stream.

Reducing or banning chlorine in plastics is an option that could reduce dioxin burden on the environment considerably. PVC has one of the highest tensile strengths and stiffness or modulus of elasticity of commonly available low-cost plastics, and is employed extensively in long-term (15-30 year life) applications in building materials for floor covering, electrical insulation, water pipes, window frames, and air supply ducts, the medical industry, and general use in automobile and appliance parts. Converting to non-chlorinated plastic resins would lead to increased costs, but this would be offset by reduced dioxin burden for thermochemical processes (the degree of offset would have to be investigated). Replacement of industrial/consumer product components with more environmentally benign alternatives is not without precedent. Outright banning of CFC propellants and refrigerants in 1996 is one example.

C&D Lumber and Green Wastes

Construction and demolition (C&D) waste wood is landfilled at an estimated annual amount of 2 million tons (about 5 % of total landfill stream by mass). Leaves, grass, prunings, trimmings, and "other biomass organics" are generally referred to as the green waste stream. Together, these components contribute some 6.9 million tons annually to California landfills (~17 %). The amount of these materials that currently are being diverted is difficult to know. Many of the existing biomass power facilities in the state receive urban waste wood for a portion of their fuel. Compost feedstock and alternative daily cover (ADC) account for the remainder of diverted green and woody waste material. The 2004 CIWMB report *Assessment of California's Compost- and Mulch-Producing Infrastructure*[37] identified approximately 8 million tons per year of green and woody material are processed in compost or other facilities. Some of the biomass power urban wood fuel stream is accounted for in this report but it is not known if all the diverted wood waste was accounted for.

Nonetheless, the 6.9 million tons of this waste stream currently landfilled is material acceptable to both thermochemical and biochemical conversion means. The drier material may be better suited

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[†] "Tertiary Recycling" processes that depolymerize the material and convert to chemicals or fuels can accept some plastic mixtures.

for thermochemical conversion. Either hydrogasification or biochemical methods of conversion may be easier to apply to wet wastes.

Food in the Landfill Stream

Food wastes are estimated to be landfilled in the amount of 5.9 million tons annually in California. The amount of waste food that is diverted was not determined. Some jurisdictions may have reliable recent information of food waste diversion rates. Waste food, fats, oils, and greases (FOG) are prime candidates for biochemical conversion because they have high bio-methane potential (BMP), due in part to the low cellulose and lignin amounts in food waste (compared with green waste). Also, the high moisture content of most food waste makes it undesirable for most thermochemical conversion systems. The precommercial method of hydrogasification has been used to process wet food waste and plastic waste together without the need for separation or drying.

Source separated food wastes are the best feedstock for biochemical conversion (especially AD or "biogasification" methods). Most kitchen waste in California could be ground and passed into waste water systems for biological digestion using the existing installed base of garbage grinders, without any additional capital cost. Appropriate financial incentives, such as tax credits to pay for regular residential sewer line maintenance, and periodic equipment replacement, may be need to encourage wider use of this methods of disposal for food waste.

2.3 Feedstock Characteristics

Performance, efficiency, product (and residue) mix and amount are only a few of the many parameters of a conversion technology that are affected by feedstock characteristics. Depending on the complexity of the MSW conversion process, knowledge of feedstock composition as well as physical and chemical characteristics of the individual component classes can be critical. Table 2-1 displays proximate and ultimate (elemental) analyses and heating value for many waste components. Heating value varies widely across the waste components with plastics and tires showing higher heating values (9500 to 20,000 Btu/lb), paper products and waste wood comprising a middle range of energy content (2900 to 8000 Btu/lb), and green or food wastes at the lower to middle range of the energy spectrum (1800 to 2600 Btu/lb).[‡] The energy content of the landfilled solid waste stream in California (all components averaged together) is 4700 Btu/lb (see Table 1-1).

Inorganic (or ash) content of feedstock material is an important characteristic because it indicates the minimum achievable solid residue (mass basis) from a process that converts 100 % of the organic (carbon containing) material. Ash content of waste stream components varies from a low of essentially zero for separately collected FOG to a high of 70 % for "household dirt." Depending on how green waste and grass clippings are collected and stored before use, the "as received" ash content can vary from 1 % to as high as 30 %. The variability is due essentially to the amount of dirt or other inorganic material present in the green waste. While most paper products have ash contents below 6 %, magazines and other glossy colored paper items have ash content near 25 % due to the clay content and the amount of ink used. Plastic items are generally low in ash content. Mixed plastics have a higher ash content because generally dirt, paper labels,

[‡] These are heating values for the components in their "as received" or moist condition.

Table 2-1: Proximate and Ultimate Analysis and Heating Value of Waste Components[38]

Waste Component	Proximate Analysis (Wt. %, as-received)				Ultimate Analysis (Wt. %, dry)						Higher Heating Value (Btu/lb)		
	Moisture	Volatile Matter	Fixed Carbon	Non-Comb.	C	H	O	N	S	Non-comb.	As Received	Dry	Moisture and Ash Free
Paper and Paper Products													
Paper, Mixed	10.24	75.94	8.44	5.38	43.41	5.82	44.32	0.25	0.2	6	6801	7572	8055
Newsprint	5.97	81.12	11.48	1.43	49.14	6.1	43.03	0.05	0.16	1.52	7974	8480	8600
Brown Paper	5.83	83.92	9.24	1.01	44.9	6.08	47.34	0	0.11	1.07	7255	7705	7799
Trade Magazine	4.11	66.39	7.03	22.47	32.91	4.95	38.55	0.07	0.09	25.43	5256	5479	7151
Corrugated Boxes	5.2	77.47	12.27	5.06	43.73	5.7	44.93	0.09	0.21	5.34	7044	7430	7851
Plastic-Coated Paper	4.71	84.2	8.45	2.64	45.3	6.17	45.5	0.18	0.08	2.77	7342	7702	7942
Waxed Milk Cartons	3.45	90.92	4.46	1.17	59.18	9.25	30.13	0.12	0.1	1.22	11,328	11,733	11,892
Paper Food Cartons	6.11	75.59	11.8	6.5	44.74	6.1	41.92	0.15	0.16	6.93	7258	7731	8250
Junk Mail	4.56	73.32	9.03	13.09	37.87	5.41	42.74	0.17	0.09	13.72	6088	6377	7401
Food and Food Waste													
Vegetable Food Waste	78.29	17.1	3.55	1.06	49.06	6.62	37.55	1.68	0.2	4.89	1795	8269	8700
Cirtus Rinds and seeds	78.7	16.55	4.01	0.74	47.96	5.68	41.67	1.11	0.12	3.46	1708	8016	8301
Meat Scraps (cooked)	38.74	56.34	1.81	3.11	59.96	9.47	24.65	1.02	0.19	5.08	7624	12,446	13,110
Fried Fats	0	97.64	2.36	0	73.14	11.54	14.82	0.43	0.07	0	16,467	16,467	16,467
Mixed Garbage I	72	20.26	3.26	4.48	44.99	6.43	28.76	3.3	0.52	16	2372	8483	10,100
Mixed Garbage II	-	-	-	-	41.72	5.75	27.62	2.97	0.25	21.87	-	7248	9261
Trees, Wood, Brush, Plants													
Green Logs	50	42.25	7.25	0.5	50.12	6.4	42.26	0.14	0.08	1	2103	4206	4251
Rotten Timbers	26.8	55.01	16.13	2.06	52.3	5.5	39	0.2	1.21	2.8	4711	6370	6558
Demolition Softwood	7.7	77.62	13.93	0.75	51	6.2	41.8	0.1	<.1	0.8	7300	7916	7997
Waste Hardwood	12	75.05	12.41	0.54	49.4	6.1	43.7	0.1	<.1	0.6	6429	7300	7342
Furniture Wood	6	80.92	11.74	1.34	49.7	6.1	42.6	0.1	<.1	1.4	7349	7815	7942
Evergreen Shrubs	69	25.18	5.01	0.81	48.51	6.54	40.44	1.71	0.19	2.61	2709	8736	8962
Balsam Spruce	74.35	20.7	4.13	0.82	53.3	6.66	35.17	1.49	0.2	3.18	2446	9542	9850
Flowering Plants	53.94	35.64	8.08	2.34	46.65	6.61	40.18	1.21	0.26	5.09	3697	8026	8460
Lawn Grass I	75.24	18.64	4.5	1.62	46.18	5.96	36.43	4.46	0.42	6.55	2058	8314	8901
Lawn Grass II	65	-	-	2.37	43.33	6.04	41.68	2.15	0.05	6.75	2689	7692	8250
Ripe Leaves I	9.97	66.92	19.29	3.82	52.15	6.11	30.34	6.99	0.16	4.25	7984	8868	9270
Ripe Leaves II	50	-	-	4.1	40.5	5.95	45.1	0.2	0.05	8.2	3535	7070	7702
Wood and Bark	20	67.89	11.31	0.8	50.46	5.97	42.37	0.15	0.05	1	6898	8612	8700
Brush	40	-	-	5	45.52	5.9	41.2	2	0.05	8.33	4744	7900	8600
Mixed Greens	62	26.74	6.32	4.94	40.31	5.64	39	2	0.05	13	2689	7077	8136
Grass, Dirt, Leaves	21-62	-	-	-	36.2	4.75	26.61	2.1	0.26	30.08	-	6283	8988
Upholstery	6.9	75.96	14.52	2.62	47.1	6.1	43.6	0.3	0.1	2.8	6960	7478	7689
Tires	1.02	64.92	27.51	6.55	79.1	6.8	5.9	0.1	1.5	6.6	13,800	13,907	14,902
Leather	10	68.46	12.49	9.1	60	8	11.5	10	0.4	10.1	7961	8852	9850
Leather Shoe	7.46	57.12	14.26	21.16	42.01	5.32	22.83	5.98	1	22.86	7245	7828	10,152
Shoe, Heel & Sole	1.15	67.03	2.08	29.74	53.22	7.09	7.76	0.5	1.34	30.09	10,900	11,026	15,790

Waste Component	Proximate Analysis (Wt. %, as-received)				Ultimate Analysis (Wt. %, dry)						Higher Heating Value (Btu/lb)		
	Moisture	Volatile Matter	Fixed Carbon	Non-Comb.	C	H	O	N	S	Non-comb.	As Received	Dry	Moisture and Ash Free
Rubber	1.2	83.98	4.94	9.88	77.65	10.35	-	-	2	10	11,201	11,331	12,601
Mixed Plastics	2	-	-	10	60	7.2	22.6	-	-	10.2	14,101	14,367	16,000
Plastic Film	3-20	-	-	-	67.21	9.72	15.82	0.46	0.07	6.72	-	13,845	14,869
Polyethylene	0.2	98.54	0.07	1.19	84.54	14.18	0	0.06	0.03	1.19	19,678	19,730	20,002
Polystyrene	0.2	98.67	0.68	0.45	87.1	8.45	3.96	0.21	0.02	0.45	16,421	16,451	16,512
Polyurethane	0.2	87.12	8.3	1.38	63.27	6.26	17.65	5.99	0.02	4.38 (a)	11,205	11,224	11,733
Polyvinyl Chloride	0.2	86.89	10.85	2.06	45.14	5.61	1.56	0.08	0.14	2.06 (b)	9756	9776	10,003
Linoleum	2.1	64.5	6.6	26.8	48.06	5.34	18.7	0.1	0.4	27.4	8152	8311	11,451
Rags	10	84.34	3.46	2.2	55	6.6	31.2	4.12	0.13	2.45	6898	7653	7845
Textiles	15-31	-	-	-	46.19	6.41	41.85	2.18	0.2	3.17	-	8036	8301
Oils, Paints	0	-	-	16.3	66.85	9.63	5.2	2	-	16.3	13,402	13,402	16,000
Vacuum Cleaner Dirt	5.47	55.68	8.51	30.34	35.69	4.73	20.08	6.26	1.15	32.09	6386	6756	9960
Household Dirt	3.2	20.54	6.26	70	20.62	2.57	4	0.5	0.01	72.3	3671	3791	13,651
Municipal Wastes													
Street Sweepings	20	54	6	20	34.7	4.76	35.2	0.14	0.2	25	4802	6001	8000
Mineral (c)	2-6	-	-	-	0.52	0.07	0.36	0.03	0	99.02	-	84	-
Metallic (c)	3-11	-	-	-	4.54	0.63	4.28	0.05	0.01	90.49	-	742	7799
Ash	10	2.68	24.12	63.2	28	0.5	0.8	-	0.5	70.2	3762	4173	14,001

a – Remaining 2.42 % is chlorine

b – Remaining 45.41 % is chlorine

c - Heat and organic contents from labels, coatings, and remains of contents on containers and other items are present. Non-combustibles, such as glass, ceramics, and metals, can conglomerate in the bed of a thermal reactor causing restricted flow and fouling. To the extent possible, removal of the non-combustibles from a CT feedstock is usually desired.

It is also important to understand contaminants that may exist in the MSW stream. Heavy metal contaminants are found in many paper products in the ink, dyes, and solvents used in paper and print production (Section 2.2). In leather production, chromium is used in the tanning process and, therefore, when leather is processed large amounts of chromium are to be expected in the slag or ash. Table 2-2 shows a distribution of the metal content in a collection of household waste. These metals will concentrate in the flyash or, for more volatile metals such as mercury, they must be removed from the flue gas.

Table 2-2: Percentage Distribution of Metal Content in Various Household Waste Fractions[39]

Fraction	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Zn
Plastics	26	1	5	2	10	1	1	5	1
Paper	4	5	7	11	13	18	3	3	11
Animal Matter	1	1	1	1	2	1	1	1	1
Vegetable Matter	2	1	2	3	6	4	3	2	4
Textiles	1	1	1	2	4	1	1	1	1
Rubber / Leather	4	1	42	1	3	1	1	2	9
Metals	60	88	43	22	60	74	87	85	68
Miscellaneous	3	4	3	63	3	4	6	4	6

Waste paper processing is also vexing due to the amount of heavy metals contained in the dyes and solvents used in paper production and printing. Lyons and Kerstetter showed values of zinc, manganese, copper, and barium were relatively high in mixed paper samples (Tables 2-3).

Table 2-3: Heavy Metal Analysis of Mixed Paper Samples[40]

	Heavy Metal Concentrations (mg/kg, dry basis)														
	Avg	Min	Max	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Arsenic	0.48	0.00	0.93	0.29	<0.06	<0.06	0.07	<0.06	0.93	0.84	0.90	0.57	0.82	0.75	0.60
Barium	46.21	2.50	92.70	2.50	22.00	24.90	24.10	27.20	48.70	57.20	70.80	57.40	61.80	65.20	92.70
Beryllium	0.70	<0.30	1.90	<0.30	<0.30	<0.30	<0.30	<0.30	1.00	1.10	1.90	1.00	1.10	1.20	1.10
Cadmium	0.55	<0.30	1.90	<0.30	<0.30	<0.30	<0.30	<0.30	0.90	1.10	1.90	0.90	0.90	<0.30	0.90
Cobalt	6.78	<0.30	14.80	<0.30	<0.30	0.30	0.60	0.50	11.20	10.40	12.10	10.30	10.00	14.80	11.10
Chromium	6.48	0.70	11.40	0.70	4.10	4.20	3.90	11.40	5.00	6.80	9.60	6.90	8.10	8.40	8.60
Copper	18.12	1.80	38.30	1.80	8.30	7.60	21.60	18.80	6.00	15.20	20.60	19.70	38.30	35.20	24.30
Manganese	27.34	7.90	86.90	7.90	9.60	12.40	20.10	18.60	11.60	24.60	30.70	23.60	86.90	52.80	29.30
Molybden	7.42	1.00	13.90	2.90	1.30	1.70	1.50	1.00	11.50	11.40	12.30	10.70	10.60	13.90	10.20
Nickel	6.92	<1	14.00	<1	1.00	<1	<1	<1	11.00	11.00	13.00	11.00	11.00	14.00	11.00
Lead	7.51	0.70	49.50	0.70	1.14	1.21	1.82	49.50	2.40	8.00	7.90	6.20	1.50	2.10	7.60
Antimony	3.88	<3	10.00	<3	<3	<3	<3	<3	7.50	7.00	8.00	6.00	4.00	10.00	4.00
Selenium	0.06	<0.06	0.13	<0.06	<0.06	<0.06	<0.06	<0.06	0.09	0.13	0.09	0.08	0.12	0.08	0.07
Tin	7.92	3.00	14.00	3.00	4.00	5.00	5.00	4.00	13.00	10.00	10.00	9.00	10.00	14.00	8.00
Zinc	149.21	8.50	837.00	8.50	837.00	38.30	36.90	47.40	9.70	116.00	116.00	34.70	298.00	81.00	108.00
Mercury	0.05	<0.05	0.33	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	0.09	0.09	<0.05	0.07	<0.05	<0.05

Note: Numbers 1-12 represent different sample numbers.

2.4 Biochemical Feedstock Characteristics

Although biochemical processes utilize only biodegradable feedstocks, different biodegradable feedstocks exhibit different performance characteristics when processed biochemically. Not all of the carbohydrate material in biomass is digestible in anaerobic systems. Cellulosic (plant based) biomass contains cellulose, hemicellulose, and lignin that combine to serve as the main structural component of the cell wall. Cellulose is a long chain polymer of glucose [$(C_6H_{10}O_5)_n$]. Cell walls contain varying amounts of hemicellulose (lower molecular weight than cellulose and with an undifferentiated structure compared to cellulose) and lignin. The amount of lignin varies with respect to plant type (it is 20%-30% in wood) but is crucial in providing rigidity to the vascular plants. Cellulose is the most abundant form of living terrestrial biomass, followed by lignin.[41] Cellulose and hemicellulose can be hydrolyzed to simple sugars and amino acids that are consumed and transformed by the fermentive bacteria. The lignin is refractory to hydrolysis and generally exits the process undigested. In fact, lignin may be the most recalcitrant naturally produced organic chemical. This is consistent with its function – to give rigidity to vascular plants that must stand upright and to protect the cellulose and hemicellulose from attack by organisms.[42] Lignin polymers are cross-linked carbohydrate structures with molecular weights on the order of 10,000 atomic mass units (amu).[µ] As such, lignin can bind with or encapsulate some cellulose making that cellulose unavailable to hydrolysis and digestion. Lignin degradation in nature is due principally to aerobic filamentous fungi that decompose the lignin in order to gain access to the cellulose and hemicelluloses.[43]

For anaerobic systems, methane gas is an important product. Depending on the type and nature of the biological components, different yields can be obtained for different biodegradable wastes. For pure cellulose, for example, the biogas product is 50 % methane and 50 % carbon dioxide. Mixed waste feedstocks yield biogas with methane concentrations of 40-60 % (by volume). Fats and oils can yield biogas with 70 % methane content.

The ultimate biochemical methane potential (BMP) of organic feedstocks can be systematically determined using a standardized method developed by Owen (1979).[44] It is analogous to the biochemical oxygen demand (BOD) assay used in water quality analysis that essentially determines the biodegradability of a liquid sample in aerobic conditions. The BMP assay involves batch digestion of a substrate under ideal anaerobic digestion conditions that include:[45]

- Broad spectrum inoculum.
- Excess inoculum.
- Excess nutrients- substrate concentration below inhibitory levels.
- Excess buffering capacity.
- Moderate and controlled temperature.
- Strict anaerobic conditions.

The method has been widely applied to determine ultimate methane potential from a variety of feedstocks.[46,47,48,49,50] The assays were obtained by using batch reactors with volumes between 2

[µ] A single water molecule (H_20) has a molecular weight of ~ 18 amu.

and 5 liters and operated at mesophilic (95ºF) temperature. Gas production was measured periodically throughout the incubation period (60-80 days) and analyzed to determine the methane concentration. Methane production results are typically reported as total liters of CH_4 produced per gram of volatile solid (VS) introduced to the reactor (liter per gram VS), as shown in Table 2-5. This table also displays methane production in units of mass and energy per mass of VS input and methane energy per mass of total feedstock input in a few cases.

The BMP assays for the feedstocks shown in Table 2-4 are listed in order of decreasing BMP. The BMP of the feedstocks reviewed range from 0.94 liters CH_4 per gram VS for vegetable oil to 0.10 liters CH_4 per gram VS for newsprint (the feedstock MSW 3a was the digestate from a pilot scale SEBAC reactor showing that there is still some BMP associated with the output of practical systems). Vegetable oil is converted to methane very efficiently because there is no lignin in processed vegetable oils and effectively all of the carbohydrate is available to hydrolysis. Also note the energy content of the methane generated from vegetable oil is more than 37 MJ/kg of VS input. The HHV of vegetable oil itself is approximately 39.6 MJ/kg. Newsprint by itself is a poor feedstock for anaerobic digestion because it contains a high amount of lignin (in the range of 20-25 % by dry weight). The HHV of newsprint is approximately 19.5 MJ/kg.

Office paper has very little lignin and, therefore, the VS material is nearly all cellulose and hemicellulose. The BMP assays for pure cellulose and office paper are essentially identical. Food wastes are good candidates for anaerobic digestion especially if they can be separated from other waste components at the source.

The MSW feedstocks reviewed in Table 2-4 are highly variable and difficult to characterize precisely. They all had major inert components removed (glass, metal and some plastic). They are probably representative of typical mixed MSW that have varying amounts of sorting applied and food waste type and amount that varies by region and/or season. The methane potential for these samples varied from 0.13 to 0.16 grams CH_4 per gram VS.

Table 2-4 Biochemical Methane Potential (BMP) of Selected Feedstocks*

	Source*	% TS	VS/TS (x 100%)	Bo‡- CH_4 (average of 3 or 4 replications) (l/ gVS)	(g/g VS)	CH_4 Energy (MJ/kg VS)	CH_4 Energy (MJ/kg input)
Vegetable oil	a			0.94	0.67	37.27	
Primary sludge	a			0.59	0.42	23.39	
Food waste	a			0.54	0.39	21.41	
Kelp	a			0.40	0.29	15.86	
Avicel Cellulose	a			0.37	0.26	14.67	
Office paper	b	96.2	92.7	0.37	0.26	14.63	13.05
Poplar	a			0.28	0.20	11.10	
Corrugated paper	b	94.8	97.7	0.28	0.20	11.02	10.21
Sugarcane	a			0.27	0.19	10.70	
MSW 2	b	63.6	79.7	0.22	0.16	8.80	4.46
Willow	a			0.22	0.16	8.72	
MSW 3	b	100	84.1	0.22	0.15	8.52	
MSW 1	a			0.21	0.15	8.33	
Grass	b	37	88.1	0.21	0.15	8.29	2.70
MSW 4	b	100	92.5	0.21	0.15	8.13	
MSW 5	b	100	94.1	0.19	0.13	7.37	
Blend of grass, leaves, branches	b	50.4	92	0.14	0.10	5.67	2.63
Branches	b	70.8	93.9	0.13	0.10	5.31	3.53
Leaves	b	56.4	95	0.12	0.09	4.88	2.61
Newspaper	b	92.2	97.6	0.10	0.07	3.96	3.57
MSW 3a	b	100	72.9	0.05	0.03	1.78	

Material	Description
MSW 1	Described as MSW - non-classified
MSW 2	Obtained from a Sumter Co., FL compost facility (sample supplied was not composted). The facility processed MSW using mechanical removal of ferrous matl., manual removal of Al and some plastic followed by shredding in hammermill. About 60% paper and 6% yard waste.
MSW 3	Same source and collection day as MSW 2 (but different sample) and oven dried to 0% moisture
MSW 3a	MSW 3 digestate from the SEBAC process
MSW 4	Obtained 3/7/1990 from a MRF in Levy, Co., FL. Mixed MSW was hand-sorted to remove metal, glass, plastic and fabrics. Remaining matl. was primarily paper (92%), cardboard (4%) then yard and food waste. Matl. was shredded in a hammermill.
MSW 5	Similar to MSW 4. Obtained 3/14/1990 from a MRF in Levy, Co., FL.

‡ Bo is biochemical methane potential (methane gas at STP, 1 atm, 0 C)
*Sources;
a)Chynoweth, D. P., Turick, C. E., Owens, J. M., Jerger, D. E., and Peck, M. W. (1993). "Biochemical methane potential of biomass and waste feedstocks." Biomass and Bioenergy, 5(1), 95-111.
b) Owens, J. M., and Chynoweth, D. P. (1993). "Biochemical Methane Potential of Municipal Solid-Waste (Msw) Components." Water Science and Technology, 27(2), 1-14

3 Conversion Technology Processes

Conversion technologies refers to those processes and methods that do not employ full oxidative combustion (commonly called incineration). These include thermochemical processes, such as pyrolysis and gasification, and biochemical processes, such as anaerobic digestion, aerobic digestion, and fermentation. Plasma arc and catalytic cracking are specific processes within the thermochemical conversion category (and are reviewed). General definitions for each of these processes are provided in Chapter 1. In this chapter, descriptions of each of the thermochemical and biochemical process are provided along with a general discussion of the current status of the various technologies. More detailed descriptions of individual technologies and their current status of commercialization is provided in the appendices. Appendices D-F, respectively, describing separately conversion processes based on, straight pyrolysis technologies, technologies that combine pyrolysis and gasification, and straight gasification technologies. Appendices G and H describe plasma arc conversion processes and biochemical conversion processes, respectively.

3.1 Thermochemical Conversion Processes

3.1.1 Overview of Pyrolysis

Pyrolysis is an endothermic process in which material is thermally decomposed without the addition of air or oxygen. Pyrolysis produces fuel gases[*] (a mixture of methane and higher molecular mass hydrocarbon gases or vapors that can be used for combustion but not for liquid fuel or chemical synthesis without further upgrading) and solid chars from solid feedstocks. Pyrolysis can also be optimized for the low-cost production of fuel liquids (pyrolysis oils) that can be used without additional processing (e.g., as a boiler fuel) or, with the expenditure of additional energy for distillation and refining, for higher quality uses such as engine fuels, chemicals, adhesives, and other products. The pyrolytic product gases are typically of medium heating value and the pyrolytic vapors (or condensed liquids or oils) are usually complex mixtures of hydrocarbons, which must be upgraded for conversion to chemicals or liquid fuels. Condensed pyrolysis vapors from biomass include water that may need removal prior to use.

High temperature processes that thermally decompose materials without the addition of any air or oxygen are considered pyrolysis. The emphasis of the process design is typically on the deployment of a simple conversion process that can decompose the feed material into a mix of energetic compounds with minimum capital cost. Pyrolysis and combustion of pyrolysis-derived fuels such as solid chars, liquids and gases also produce the same categories of end products as direct combustion of solids, although the emission byproducts can be more readily controlled.

Gasification

Gasification usually refers to the high fraction[θ] conversion of solid carbonaceous materials to gases via either direct heating by partial oxidation of the material to be gasified, using substoichiometric air or a pure oxygen feed, or by indirect heating to produce synthesis gas (CO and H_2) and some fuel gas (principally methane, and lighter hydrocarbons), in addition to the inert gases CO_2 and N_2 and water vapor, depending on process used. Incomplete gasification

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[*] Synthesis gas is a mixture of hydrogen and carbon monoxide that can be used directly in fuel and chemical synthesis that is almost uniquely produced by gasification and reformation
[θ] Typically between 85 to 95% of the carbon in the feed

processes can produce energetic liquids (tars, oils, and other condensates) and solid residues (char, ash) from the original solid feedstocks. In many ways, incomplete gasification is very close to pyrolysis. Complete gasification processes are designed to generate fuel or synthesis gases as the primary product, leaving the inert solid residues such as ash, sand, alumina, metals and ceramics.

Unlike pyrolysis, gasification is a reactive process that involves a gasification agent. The devolatilization of carbonaceous materials during pyrolysis in an inert atmosphere results in gases (mainly CO_2, H_2, CO, CH_4, C_2H_x, etc.) liquids (organic vapors, water and tar) and solids (char and unreacted residues). Gasification is the reactive process of transforming the pyrolytic oils and chars at elevated temperatures and a range of possible pressures into useful gaseous products, thus maximizing the production of fuel gases, and minimizing the production of energetic liquids and solids. Gasification agents such as air, oxygen, steam, CO_2, and H_2 are often used.

An important aspect of gasification is that the chemical reactions can be controlled to control the resultant products. Some of the most important reactions that occur in char gasification with various gasification agents are provided below.[51] These equations will not be discussed in detail here, but are provided to show different aspects of the gasification reaction. The first four reactions, equations (1-4), are considered to be the most significant, and show some of the differences due to different reactants such as H_2O or H_2.

Pyrolysis of biomass usually produces CO and CO_2 from the elemental oxygen present in the feedstock, as shown in equations (1-3). These reactions all require energy to occur (this is indicated by the positive value of the enthalpy of reaction $\Delta H^{\circ\dagger}$). This energy may be provided through the gasification in one of two ways: 1) either by oxidation of part of the carbonaceous feed, utilizing equations (7-8), or 2) by reduction of the feedstock using high partial pressures of hydrogen (equations 4 and 6).

$C + CO_2 = 2CO$	$\Delta H° = +172$ kJ	(1)
$C + H_2O\ (g) = CO + H_2$	$\Delta H° = +130$ kJ	(2)
$C + 2H_2O\ (g) = CO_2 + 2H_2$	$\Delta H° = + 88$ kJ	(3)
$C + 2H_2 = CH_4$	$\Delta H° = - 71$ kJ	(4)
$CO + H_2O\ (g) = CO_2 + H_2$	$\Delta H° = - 42$ kJ	(5)
$CO + 3H_2 = CH_4 + H_2O\ (g)$	$\Delta H° = -205$ kJ	(6)
$C + 1/2\ O_2 = CO$	$\Delta H° = -109$ kJ	(7)
$C + O_2 = CO_2$	$\Delta H° = -390$ kJ	(8)

Partial oxidation of the carbonaceous feed is the most common method to provide heat directly to the feed for gasification, often consuming between 20 % and 35 % of the feed mass flow to provide the energy needed to pyrolyze the rest. The high rates of heat transfer achievable during the partial oxidation process within the gasifier are such that this process is often considered an

† ΔH° is the enthalpy of reaction for 1 mole of the pure substance, at a temperature = 568° F, and pressure = 1 atmosphere. Negative ΔH° implies an exothermic (heat releasing) reaction, and a positive value implies an endothermic (heat consuming) reaction.

autothermal method of gasification. For pressurized gasification processes, the efficiency and expense of the process depends on (among other things) how the oxidant is obtained (whether it is from air, oxygen enriched air, or pure oxygen). The energy needed to compress the gasifying air with its associated nitrogen component, or to operate an air separation plant (for pure oxygen or oxygen enriched air), both contribute to lowering the overall energy efficiency of this method of gasification. Some improvements in thermal energy management may be possible using indirect heating of the feed in the gasifier by circulating hot inert solid particles, such as sand, from a separate externally fired heater (e.g., the FERCO gasifier).

Recently, considerable progress has been achieved using hydrogen-driven gasification, or hydrogasification, based on the methanation reaction shown as equation (4). This is an exothermic (heat-releasing) reaction and can be used to sustain gasification temperatures especially if steam pyrolysis has been used to create an activated carbon rich char having a high surface area. In addition, the exothermic reactions of carbon monoxide, equations (5 and 6), in the presence of steam and hydrogen, can provide enough additional energy to sustain the gasification of the activated carbon char without the need for partial oxidation. This process is especially useful when processing wet organic feedstcoks, since the cost of drying the feed is unnecessary.

The gases produced by gasification can be cleaned to remove unwanted particulates and compounds, and then used as fuels in internal and external combustion engines, fuel cells, and other prime movers. The synthesis gas products of gasification can be used to create liquid fuels such as methanol, Fischer-Tropch (FT) liquids, and other fuels and chemicals. The gasifier itself generates no air emissions, but there are usually air emissions generated from the use of the product gases or liquids (i.e., close coupled combustion of product gas for heat will yield products of combustion. If the gasifier product is used to create liquid fuels, they will generate air emissions at a later time and place when used). If process heat is needed for power conversion, then combustion of gasification-derived fuel gases can generate the same categories of exhaust products as the direct combustion of the carbonaceous feeds into the gasifier, but pollution control and conversion efficiencies may be improved, since the gasifier effluent flow is often less than half the quantity of flow in the direct combustion exhaust effluent (see Table 4-5 for typical gas product compositions).[52] This results in potentially lower costs of emissions control via improved combustion or post-combustion clean-up from gasification effluent compared to the controlling of emissions from direct combustion. Additional cost savings can also be found in reduced high temperature corrosion on heat exchanger and boiler surfaces.

3.1.2 Process Description

Pyrolysis

The system design for different pyrolysis units can differ between different manufacturers. The overall processing of waste using pyrolysis does include a number of common steps between the different processes. These general steps include feedstock preparation and introduction into the reactor, the pyrolysis reaction step, post-combustion or processing of the gases produced during pyrolysis, and the handling of the resulting pyrolytic oils, char, and ash (Figure 3-1). This section briefly provides an overview of the types of processes used for the various steps in the pyrolysis process.

The preparation and introduction of the feedstock into the reactor can vary depending on the specific nature of the waste being disposed. Common processes in the preparation of the feedstock include drying and shredding to promote a more favorable reaction for the material once it is in the pyrolyzer. The degree of drying is process-dependent, with some processes capable of handling moist/undried MSW or other waste and other processes with moisture requirements as low as 2%-5 %. For MSW, an additional processing step is often used for recovered metal and glass components that might be recyclable or are inert in the pyrolysis or post-combustion reactors. Upstream sorting processes can also be used for the removal of more moist organic materials to help provide a fuel with a lower moisture content. Sorted MSW can also be pellitized into a refuse-derived fuel.

The feedstock can be introduced into the reaction chamber by a number of methods including gravity feeding, pressing using a screw auger or other device, or other methods such as bottom feeding with mixing via centrifugal forces or through the use of containers for the waste. In many cases, the waste material is introduced into the reactor using an airlock system, to reduce/eliminate the introduction of oxygen into the system.

Typically pyrolysis occurs at temperatures in the range of 750-1500^{o} F. Because air or oxygen is not used in the reaction, pyrolysis usually requires an input of thermal energy, which is typically applied indirectly by thermal conduction through the walls of a containment reactor. This pyrolysis reactor is usually filled with an inert gas to facilitate the heat transfer from the reactor walls, and to provide a transport medium for removal of the gaseous and vapor phase pyrolytic products.

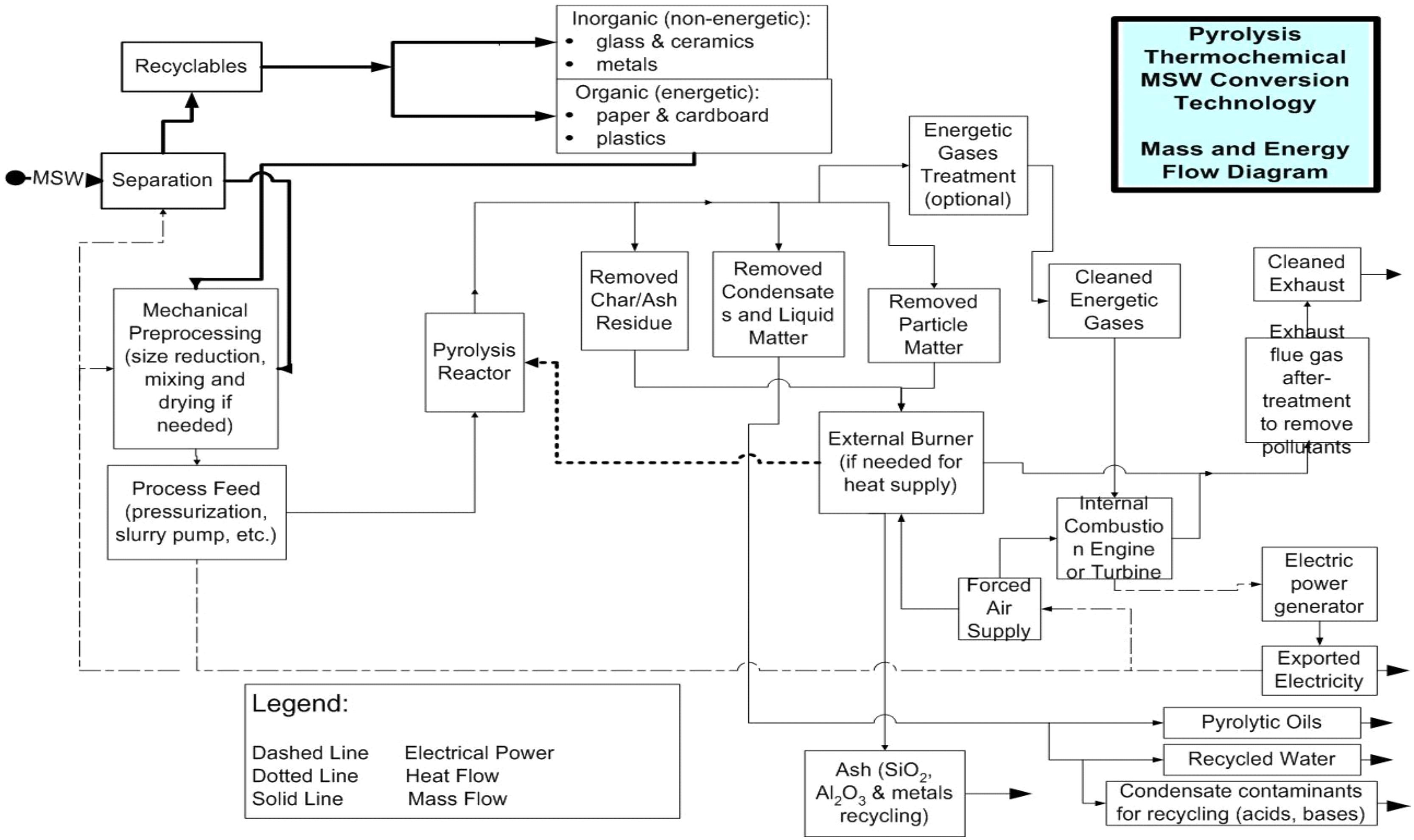

Figure 3-1: Schematic Diagram of a Pyrolysis Process.

The reaction vessel itself is one of the most variable components of the system design. The reactor type used depends on a number of variables including the type and preparation of the feedstock and the operating conditions required for the appropriate reactions. Reactors can typically be characterized as either vertical or horizontal. A rotary kiln is an example of a horizontal reactor. The three main types of vertical reactors are fixed bed, fluidized bed, and entrained bed. For the fixed bed systems, the feedstock is typically fed through the system on a grate with either up-, down-, or cross draft flow. In an updraft flow (or countercurrent) reactor, the air or oxygen supply is injected from the bottom and the effluent stream extracted from the top of the reactor vessel. In a downdraft reactor, the air or oxygen is injected through nozzles along the circumference at the top of the reactor and the effluent extracted towards the bottom of the reactor. In a fluidized bed reactor, the reactor bed is filled with inert particles (usually sand or alumina) containing some catalyst in addition to the feedstock. The feedstock and bed materials are continuously agitated during the process to provide a more uniform heating of the feedstock and improved heat transfer. Fluidized bed systems typically use air or oxygen injected into the reactor from the base of the chamber, as in gasification, to entrain solids and produce a uniform circulation of hot particles. For pyrolysis reactors, the fluidized condition can be created using recirculated gaseous products to eliminate the need for oxygen/air addition. Several types of fluidized bed reactor are utilized including a bubbling fluidized bed, circulating fluidized bed, and revolving fluidized bed. The bubbling phenomenon is related to the fluidizing velocity in the bed. A circulating fluidized bed uses fluidizing velocity above those used for bubbling, resulting in a turbulent state. Solids rejected from the bed at these velocities are then captured in a cyclone and returned to the bottom of the bed creating a circulation. Other reactor designs include open hearth, tubular and cylindrical tank reactors. A summary of pyrolysis reactor designs found for different processes that use MSW or other secondary materials is provided in Table 3-1.

Table 3-1. Reactor Designs for Pyrolysis Technologies

Reactor Type	Technology
Rotary drum	Bal-Pac, IES, Enersludge, Siemens, Waste-Gen/Technip, Thide, Serpac, PKA
Fluidized bed	Dynamotive
Tubular	Brightstar
Transport reactor	Ensyn, Von Roll
Other	GEM, Nexus, Thermoselect

The composition of the pyrolytic products can be changed by the temperature, the speed of the process, and the rate of heat transfer. Lower pyrolysis temperatures usually produce more liquid products and high temperatures produce more gases. Slow pyrolysis (carbonization) can be used to maximize the yield of solid char. This process requires a slow pyrolytic decomposition at low temperatures. A common example of this method of pyrolysis is the production of charcoal from wood feedstock. Fast or "flash" pyrolysis involves a shorter exposure (<1 second) to temperatures around 930^{o}F. Rapid quenching is necessary to "freeze" the decomposition products and condense gaseous species before simple molecules (lower molecular mass) are formed which are naturally gaseous under ambient conditions. This process results in a product that is up to 80% liquid by weight.

Hydrogen and/or steam can also be used as agents in the pyrolysis reaction. Such processes are currently at a research level for application to wastes, but have been investigated in greater detail for the processing of coal.[53] Significant differences in the pyrolytic product distribution can occur when using hydrogen[54] and/or steam[55] as the pyrolyzing media. Hydrogen gas can be used to enhance chemical reduction and suppress oxidation from the elemental oxygen in the feedstock.

This process, known as hydropyrolysis, was originally developed to enhance the production of fuel gases from the pyrolysis of coal. Water or steam can also be incorporated into the pyrolysis process to not only produce pyrolytic gases and vapors but also to increase the porosity of the resultant char. By creating a very high surface area and porosity, activated charcoal can be formed. Steam pyrolysis can also be used to achieve adequate results at lower temperatures but higher pressures than pyrolysis conducted in the absence of water, or dry pyrolysis. The results of experiments in the gasification research laboratory (GRL) at UCR CE-CERT have also shown the steam pyrolysis and the activation of the char may be used to enhance the reactivity and thermal management with hydrogen in subsequent hydrogasification processing of the char. This ability to pyrolyze and gasify wet streams of carbonaceous material using chemically reducing processes appears to have some distinct advantages over the more traditional dry and partially oxidative methods.

The gases and vapors produced during the pyrolysis reaction are often combusted or gasified in a separate reaction chamber. The thermal energy resulting from the combustion of these pyrolytic products can be used in a variety of ways, including making steam for electricity production and heating either the pyrolysis reactor or the feedstock drying process. An important component of any pyrolytic gas combustion process is the after-treatment equipment used to clean the effluent gases. Although the combustion of pyrolytic product gases is more efficient and produces less emissions than incineration of waste materials without pyrolysis, the emissions of pyrolytic gas combustion products still requires emissions control to meet regulatory standards. Standard exhaust flue gas control strategies for combustion processes include particulate filters or bag houses, wet scrubber techniques, and electrostatic precipitation. These techniques are discussed in greater detail in Chapter 5. It should be noted that since pyrolysis processes produce intermediate product gases, it is possible to apply air pollution control techniques upstream of any full combustion processing, which can provide advantages in terms of removal effectiveness and cost. Most biomass materials usually contain between 25% and 45% by mass (weight) of elemental oxygen, so some oxidative reactions will occur during pyrolysis, even though additional oxygen is intentionally excluded from the process.

The post-processing of pyrolytic liquid and solid products including bio-oils, char, and ash, is another important part of the environmental control process. At the lower temperatures often used in pyrolysis processes or upon subsequent quenching of the pyrolytic gas temperature, bio-oils can be produced. The bio-oils themselves represent a viable product that can be utilized as a fuel source in certain engine applications or as a more general product in other uses. In many of the processes surveyed, the bio-oil was reintroduced into the pyrolysis process as a fuel source for the generation of process heat. Some care may be needed in combusting the bio-oil derived from solid waste to ensure that components such as chlorine or other contaminates can be removed prior to pyrolysis or controlled through pollution control technologies after the combustion process. This is discussed in greater detail below. The char or solid carbonaceous portion of the pyrolytic residue can also be utilized as a fuel source or even sold as a product for the manufacture of activated carbon. Again, the reintroduction or use of pyrolytic char as a fuel source in the pyrolysis process is an important element of the process design for many of the technologies surveyed. The inert ash in the solid pyrolytic residual is generally not reintroduced into the process, with the exception of some processes utilizing fluidized bed reactors. In many technologies, some processing of the ash is incorporated. This could include a water wash/quenching, screening, or removal of metals. In some technologies, a vitrification step is also included whereby the ash is heated to a temperature above the fusion point of the sand with the soluble components in the ash to produce a slag residual. Additional information on the use of the solid and liquid residue is provided in Chapter 4 on products.

Gasification

The designs of gasification systems are similar to those of pyrolysis in terms of the major steps, but gasification tends to pick up where pyrolysis leaves off. Complete gasification systems are designed to completely gasify the carbonaceous feedstock into gas products. The general steps in gasification include feedstock preparation and introduction, the reaction step, and the post processing of residual products (Figure 3-2). Since the reactions go beyond the level of material devolatilization, gasification systems tend to be more complex than those of pyrolysis. At the same time, the additional control provided by the introduction of a reactant at specified temperature and pressure allows careful control of the resulting product gases.

Feedstock preparation and introduction into the reactor in gasification can utilize some of the same techniques used for pyrolysis when using air or oxygen at pressure near one atmosphere. However, gasification systems can be operated at elevated pressures to gain advantages in process efficiency and lower capital cost scaling. These advantages usually requiring more sophisticated feedstock introduction techniques.

For systems operating at elevated pressures and using a feedstock with limited moisture, or a dry feedstock, a gas filled lock hopper design is common. For elevated pressure injection, the feedstock materials are introduced through a top fill valve of a two-valve holding vessel, so that the feedstock can be injected into the reactor once the top valve is closed, the vessel is then pressurized with an inert gas, and the bottom lock hopper valve is opened to allow injection of the contents into the high-pressure gasifier. Alternatively, the feedstock can be introduced in conjunction with water or oil in the form of a slurry. This allows metered introduction of the feedstock on a more continuous basis. The water or oil can also be used in the reaction step as the gasification agent.

The reactor designs are also similar to those used for pyrolysis and include rotary drums, fluidizing beds, fixed beds, and entrained beds. A summary of some of the technologies that utilize gasifier reactor designs applied to MSW feedstock is provided in Table 3-2. While gasification processes vary considerably, typically gasifiers operate at 1300° F and higher. Gasification reactors can also be multi-staged such that they include both a pyrolysis and a gasification step. Finally, a number of gasification processes are designed to operate at pressures above one atmosphere. The advantage of high-pressure operation is that the reaction rate can be increased without substantially increasing the size of the reaction vessel. This improves scalability and thermochemistry by allowing units with larger throughputs to be designed more compactly with adequate chemical kinetics, without going to higher temperatures. The addition of a reactive gasification agent also differs from pyrolysis systems in that air, oxygen or reactive gases are added to the process. The use of air provides a less complex system, but results in diluted product gases with a lower energy content due to the presence of excess nitrogen. For applications with higher gasification temperatures or at elevated pressures of greater than 5 atmospheres, pure oxygen is typically used instead of air. The need for an air separation system to provide the high-pressure purified oxygen adds cost and complexity to the partial oxidation gasification design. Hydrogen has been used with beneficial results at 25 atmospheres. One advantage of high hydrogen pressures when gasifying biomass materials is suppression of the oxidation of the carbon by the elemental oxygen already in the biomass materials, and the increased production of hydrocarbon gases. The net result of this high-pressure hydrogasification effect, is higher carbon conversion to energetic gases, when compared to alternative gasification technologies.

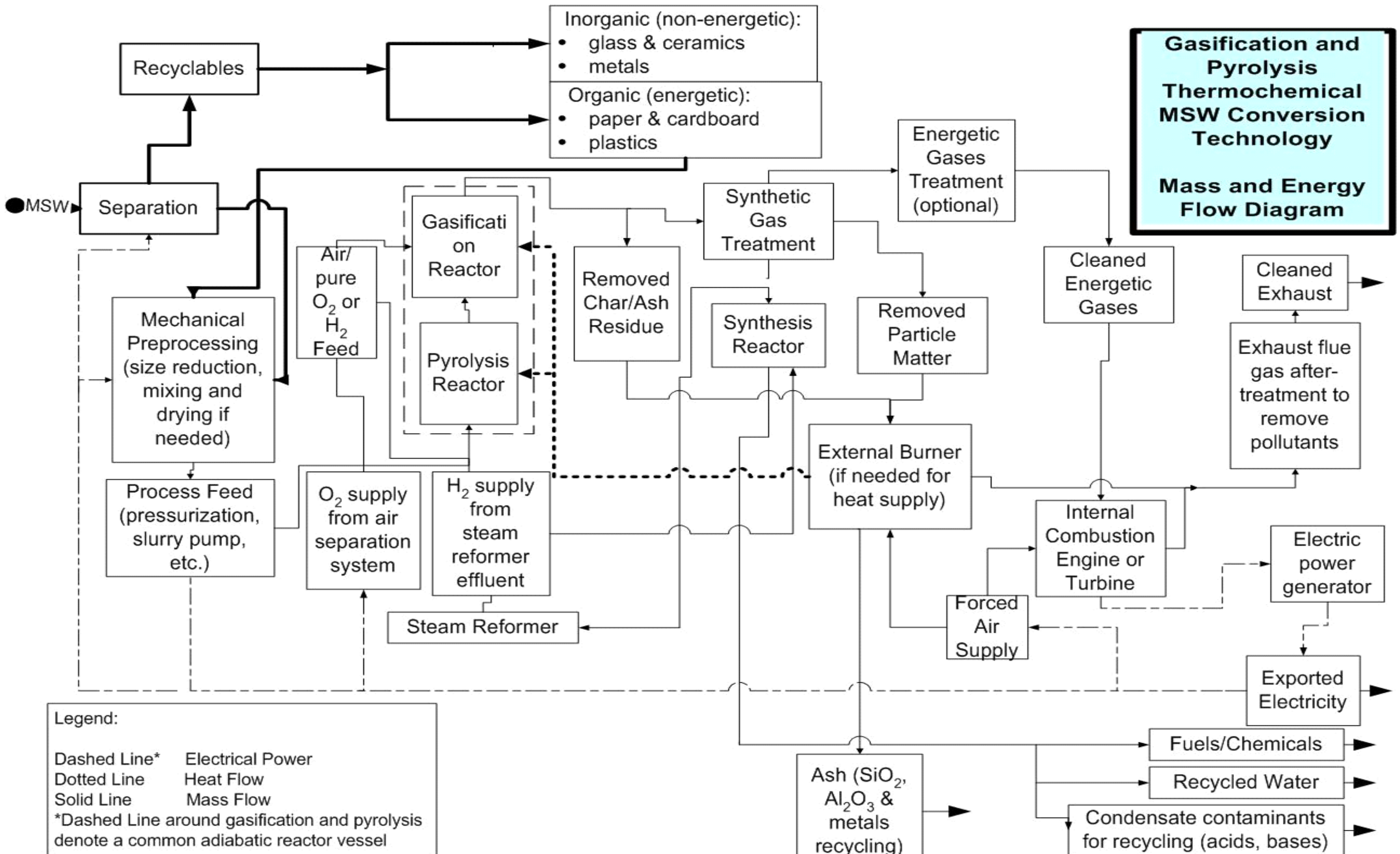

Figure 3-2: Schematic Diagram of Gasification Process with Front End Pyrolysis Process.

Table 3-2. Reactor Designs for Gasification Technologies

Reactor Type	Technology
Rotary drum	JND, WGT
Fluidized bed	Alstom/Ebara, Babcock Borsig, EPI, Enerkem, Ferco, Foster Wheeler, Lurgi, MTCI, Sumitomo, TPS
Fixed bed (downdraft)	B9, BG Systems, Heuristc, Waste to Energy
Fixed bed (updraft)	IET, Lurgi BGL, Nippon Steel, Organic Power, PRM Energy, RGR Ambiente, Thermogenics, Wellman
Entrained flow	Kvaerner Chemrec, Noell, Texaco
Tubular	Lurgi LR, Waterwide UCR CE-CERT Hydrogasification
Transport reactor	PKA Coras-H, Resorption
Melting/plasma	Nathaniel, Westinghouse Plasma, Hitachi Metals
Other	GEM, Nexus, Thermoselect

The gas products of the gasification reaction can vary in composition and energy content depending on the feedstock, the gasification agent and other system parameters. The product gas from the typical biomass-based feedstocks, such as most municipal wastes that have had plastics, metals, and glass removed, is typically a mixture of hydrocarbons, carbon oxides, hydrogen and water vapor. The product gas can have a relatively low calorific value (CV), typically 108 to 269 Btu/scf (the CV of natural gas is about 1048 Btu/scf) when using low-cost air-blown atmospheric pressure gasifiers. These gas products, after cleaning to remove residual particles, can be used as a fuel in boilers, reciprocating engines or gas turbines. When using pure oxygen or hydrogen in the gasifier, the resulting product gases will have a higher CV (typically 269 to 403 Btu/scf for oxygen blown, and 672 to 806 Btu/scf for hydrogen blown) when compared to the syngas formed using air, due mainly to the absence of nitrogen.

One of the primary objectives for complete gasification is the production of very low quantities of energetic liquids or residual solids. By achieving these objectives, removal of contamination is focused on gas cleanup technologies, rather than the cleanup of liquids and solids. For most waste feedstocks, especially when using dry pyrolysis and partial oxygen gasification heating, the resultant gas products will contain tars and particulate matter, which may need to be removed or treated before the gas is suitable for combustion. The degree of this contamination will depend on the gasification technology used and characteristics of the feedstock. High gasification temperature is the most common way to reduce the formation of tars/oils, although this can lead to higher thermal losses. Downdraft flow in fixed bed gasifiers is also designed to minimize tar and oil formation. The use of steam pyrolysis and hydrogasification also appears to reduce the formation of contaminating tars and particulate matter in the syngas produced.[56]

The degree of gas cleaning required for the fuel gas for heat or power depends on the prime mover to be used. For close-coupled (direct) combustion of the fuel gas (sometimes referred to thermal oxidation), in a furnace or boiler, essentially no cleanup of the fuel gas is required (though appropriate flue gas and emissions controls would be required downstream of the boiler/furnace). Alternatively, some emissions controls can be applied directly to the fuel gas prior to eliminate the possibility of pollutants such as dioxins and furans. Use of fuel gas in reciprocating engines requires cleaning to bring tar and particulate matter levels to below 50 and 100 mg/Nm^3 respectively (Nm^3 is "Normal cubic meter").[57] Gas turbines have more stringent requirements for fuel gas quality. Particulate matter limitations depend on the particle size, but for the size range between 10 and 20 micrograms (μm) the particle loading rate should be less than 1.2 mg/Nm^3. Alkali content should be less than 0.1mg/Nm^3. Tar content depends on the method of gas compression prior to entering the gas turbine. If an atmospheric pressure gasifier is used, followed by gas compression, then tar levels should be below 50 mg/Nm^3 to prevent compressor problems. If the gasifier is operated at the pressure required by the gas turbine, then the system is tolerant to tars. In the past, flue gas cleaning has typically been done by cooling the gas stream prior to use in the gas turbine. Significant improvements have been reported in the methods and large-scale testing of hot gas cleanup system applied to large-scale biomass gasification systems.[58] However, gas cleaning and solid fuel feeding to pressurized reactors are still economically or technically limiting factors in biomass gasification processes to produce fuel gases for gas turbines, engines, and fuel cells and much developmental work needs to continue.

Integrated gasification combined cycle (IGCC) process is another configuration that is used to improve the efficiency of conversion to electricity for some current coal and coke gasification systems. IGCC systems incorporate a gas turbine that can be used to produce electricity by internal combustion in the gas turbine, provided the gas stream can be cleaned appropriately. The heat in the hot exhaust gases from the gas turbine and other parts of the gasification system is recuperated to produce superheated steam for additional power generation using a high pressure steam turbine, as part of a comprehensive heat recovery process. IGCC has been typically applied to clean coal gasification as part of the effort to remove the chemical contaminants from coal before combustion. Some applications of IGCC have also been attempted for biomass gasification. The high cost of IGCC systems can be justified to provide net electrical efficiencies of over 30%, increasing to over 40%, if total thermal power is over 50 MW. Supercritical steam systems can also achieve high efficiencies, but at higher cost in their present stage of development. IGCC power conversion can also achieve low emissions levels for SO_2 and NO_x and the flue gas streams have small volumes when cleaned before combustion. One of the main disadvantages of these systems is the need for an expensive gas cleanup system to control the corrosive compounds such as tar, acid gases, and alkali metals in the gas phase, before entering the gas turbine. The additional system complexity when compared to externally fired steam turbine systems, can add considerably to the overall system cost.

Plasma Arc

Plasma arc is a heating method that can be used in pyrolysis or gasification systems. The technology was developed for the metals industry in the late 19th century. In recent decades, the technology has been adapted to treat hazardous radioactive waste because of the ease at which it vitrifies the residues making them less susceptible to leaching to ground water when buried. The main advantage of using a plasma is that it generates intense heat and very high temperatures. This unique characteristic provides applications in lighting, welding, the steel industry, ceramics, and the electronics industry, hazardous waste disposal, incinerator ash melting, and recently MSW conversion.

Plasma is a collection of free-moving electrons and ions that is typically formed by applying a large voltage across a gas volume at reduced or atmospheric pressure. When the voltage is high enough, and the gas pressure low enough, electrons in the gas molecules dissociate and flow towards the positive side of the applied voltage. The gas molecules (losing one or more electrons) become positively charged ions that are capable of transporting an electric current and generating heat when the electrons drop to a stable state releasing energy. This is the same phenomenon that creates lightning.

Plasma arc devices or ‘plasma torches’ can be one of two types, 1) the transferred torch and 2) the non-transferred torch. The transferred torch creates an electric field between an electrode (the tip of the torch) and the reactor wall or conducting slag bath. When the field strength is sufficiently high, an electric arc is created between the electrode and reactor (much like an automotive spark-plug). The non-transferred torch creates the electric arc internal to the torch and sends a process gas (such as air, or nitrogen) through the arc where it is heated and then leaves the torch as a hot gas (see Figure 3-3)

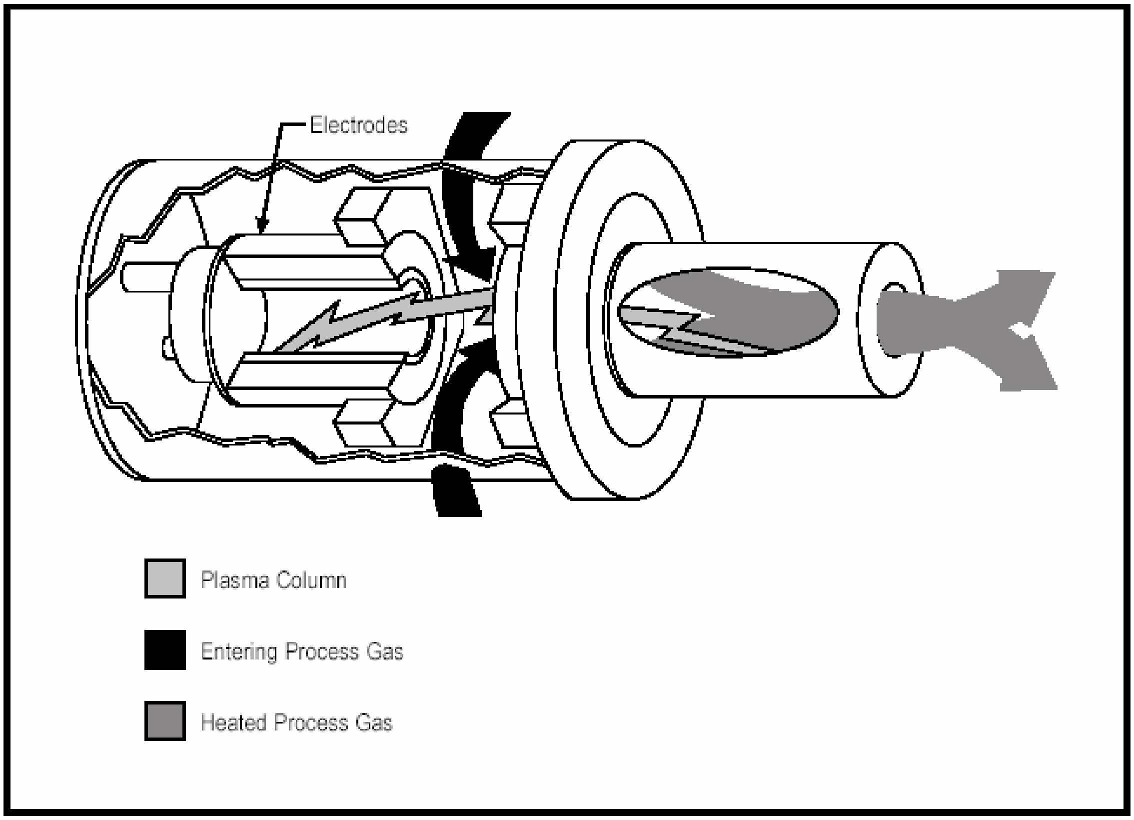

Figure 3-3: Schematic of Westinghouse non-transferred Plasma Torch (adapted from RW Beck, 2003) [59]

Very high temperatures are created in the ionized plasma (the plasma can reach temperatures of 7000º F and above; the non-ionized gases in the reactor chamber can reach 1700-2200º F; and the molten slag is typically around 3000º F). For applications in processing MSW, the intense heat actually dissociates the molecular structure of the organic material to produce simpler gaseous molecules such as CO, H_2, and CO_2. The inorganic material is vitrified to form a glassy residue. A main disadvantage of the plasma arc systems used in power generation is that a large fraction of the generated electricity is required to operate the plasma torches, which reduces net electrical output of the facility.

The plasma arc electro-thermal conversion process usually takes place in an enclosed low-pressure reaction vessel. The gases in the reactor are heated by one or more plasma torches or electrodes using a high-voltage electrical source. There are two approaches to the current design of the plasma reactors.. In the first approach, a non-transferred torch located outside of the reactor heats the process gas which is then injected into the reactor. The process gas must be at slightly higher pressure than that inside the reactor in order for the gas to flow correctly. The second approach is to locate the torch inside the reactor itself (in-situ) (see Figure 3-4).

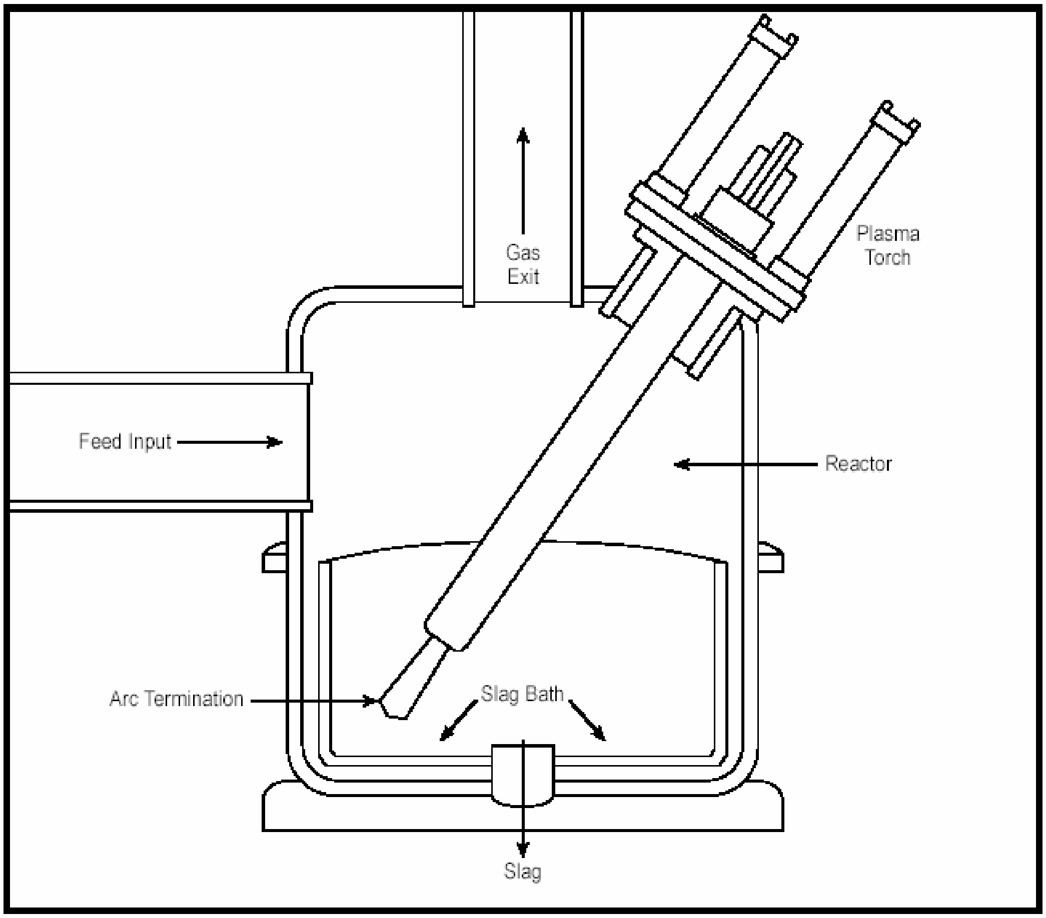

Figure 3-4 Schematic of In-Situ Plasma Torch Reactor (adapted from RW Beck, 2003)

Typically, the carbonaceous feedstock enters the reactor as a ground particulate, through a vacuum or inert gas purged lock-hopper arrangement that can remove the air and lower the pressure of the feed at the top or the side of the reactor and, after contact with the ionized or hot gas, the organic fraction pyrolyzes or gasifies with the product gas exiting the reactor (usually through the top). The metals and ash melt forming a liquid pool (slag bath) at the bottom of the reactor. The torch for an in-situ reactor can either be a non-transferred torch or a transferred torch. When using a transferred torch, the electrode extends into the waste reactor and the electric arc is generated between the tip of the torch and the conducting receiver.

Catalytic Cracking

Catalytic cracking is a subclass of thermochemical conversion usually applied to polymeric wastes to produce ethylene or liquid fuels (primarily gasoline) in an oil refinery.[60] The addition of catalysts to enhance the kinetics of this thermochemical method has created many commercial implementations that are trade secrets and proprietary. However, the deactivation of these catalysts by the chlorine present in PVC plastics makes the general application of this technology problematic without expensive sorting and pretreatment of the plastic from the MSW stream. The market for petrochemicals and polymeric materials derived from petroleum is highly competitive on a worldwide basis. The use of catalytic cracking to convert waste polymeric materials (plastics) into fuels is well established within oil refinery complexes worldwide.

3.1.3 Current Status

Pyrolysis

The use of pyrolysis for waste conversion has been ongoing since the late 1970s. A number of companies are actively promoting pyrolysis for commercial waste conversion. These companies range in size from large corporations to smaller privately owned firms. Of the facilities and designs reviewed, some technologies are already available commercially, and others are in the demonstration or development phase. In general, most pyrolysis waste conversion processes identified are operational on a scale of less than 300 TPD capacity. A listing of pyrolysis facilities that are using MSW for commercial operation is provided below in Table 3-3. The systems in Table 3-3 primarily utilize a pyrolysis reactor in conjunction with a post combustion system. Additional systems that use pyrolysis reactors followed by gasification systems are discussed below in the gasification section.

Table 3-3. Commercially Active Pyrolysis Facilities using MSW

Location	Company	Began Operation	MSW Capacity
Toyohashi City, Japan Aichi Prefecture	Mitsui Babcock	March 2002	2 x 220 TPD 77 TPD bulky waste facility
Hamm, Germany	Techtrade	2002	353 TPD
Koga Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	January 2003	2 x 143 TPD No bulky waste facility
Yame Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	March 2000	2 x 121TPD 55 TPD bulky waste facility
Izumo, Japan	Thidde/Hitachi	2003	70,000 TPY
Nishi Iburi, Japan Hokkaido Prefecture	Mitsui Babcock	March 2003	2 x 115 TPD 63 TPD bulky waste facility
Kokubu, Japan	Takuma	2003	2 x 89 TPD
Kyouhoku, Japan Prefecture	Mitsui Babcock	January 2003	2 x 88 TPD No bulky waste facility
Ebetsu City, Japan Hokkaido Prefecture	Mitsui Babcock	November 2002	2 x 77 TPD 38 TPD bulky waste facility
Oshima, Hokkaido Is., Japan	Takuma		2 x 66 TPD
Burgau, Germany	Technip/Waste Gen	1987	40,000 TPY
Itoigawa, Japan	Thidde/Hitachi	2002	25,000 TPY

Although the development of pyrolysis is ongoing throughout the world, the application of pyrolysis to the waste conversion process tends to be more developed in Japan and Europe. Japan is currently the leader in the use of pyrolysis systems for MSW. Mitsui Backbock and Takuma have both applied a pyrolysis system originally developed by Siemens (see below) to the Japanese market. Mitsui Babcock has begun operation of six facilities using its Mitsui R21 process since 2000 ranging in size from 150 to 450 TPD.[61] The first of these is at the Yame Seibu Clean Centre plant in Fukuoka, Japan, which began operation in March 2000. The largest facility is at the Toyohasi Recycle Centre in Aichi, Japan, which has two lines with a total capacity of 440 TPD. Utilizing a similar technology, Takuma now has two plants in full commercial operation for MSW with capacities of 130 to 180 tpd.[62] A third plant in Kanemura, Japan, is processing 90 TPD of ASR. Thide Environmental has licensed its process to Hitachi for

Japan.[63,64,65] Hitachi has a plant in Itoigawa, Japan, with a capacity of 25,000 TPY that has been operating since May 2002, a plant in Izumo, Japan, with a capacity of 70,000 TPY that has been operating since May 2003, and a one ton per hour pilot plant.

A number of pyrolysis processes have also been applied commercially to MSW in Europe, although the level of commercialization is less than that found in Japan and some of these facilities have experienced combinations of operational/financial problems. Nevertheless, many of the technologies being applied successfully in Japan were originally developed in Europe. One of the longest running plants for the pyrolysis of MSW is located in Burgau, Germany. This facility has been operating at a capacity of 40,000 TPY since 1987. A second facility northeast of Dortmund at Hamm in Germany began operations in 2002 with a capacity of 110,000 TPY.[66,67]

In the mid- to late 1990s, Siemens was one of the most active pyrolysis technology companies in Europe. Siemens experienced considerable problems with the continuous operation of its Fürth Plant in Germany that culminated in a serious accident at the site. The accident was reportedly due to a plug of waste that formed in the pyrolysis chamber. This resulted in over-pressurization and escape of pyrolysis gas. Some plant personnel were hospitalized and other people in the surrounding community were also admitted for observation. According to European sources, one of the main causes of the accident was poor feedstock preparation in that the unit did not utilize shredding and was accepting items as large as a full mattress with springs which caused the clog in this particular situation.[68] As a result of the problems with the Fürth plant, Siemens eventually withdrew from the market beginning in 1999. This process has subsequently been successfully used by licensees Mitsui Babcock and Takuma in Japan with some modifications, and is now one of the most successful pyrolysis technologies.

Several other technologies/facilities from Europe merit mentioning. Serpec Environmental (L'Arbresle Cédex, France) operated a 26 TPD MSW facility at the Budapest Airport from 1996 to 2003. Serpac Environmental also began operating a 45 TPD plant in Keflavic, Iceland. Graveson Energy Management (GEM) operated a facility with a 36 TPD capacity from 2000 to 2002 in the United Kingdom (UK). The reactor for this facility reportedly worked fine, although some issues were observed with an up-front autoclave system that is no longer utilized with the GEM technology. GEM also indicates that it has six facilities in various stages of development, including facilities in Spain, the U.K., and Canada. Thide-Environmental also has a 50,000 TPY facility in Arras, France that is just beginning operations.[69,70,71] Von Roll RCP has operated a demonstration plant in Bremerhaven, Germany, that had reached 8600 TPY of material in 2000.[72,73] Nexus developed a pilot laboratory in 1993 and a larger-scale demonstration plant of 5,500 TPY near Avignon, France, in 1995.[74] Pyromex currently has one 25 TPD sludge treatment facility operating in Germany since 2002 with a second 25 TPD sludge facility scheduled for commissioning in late 2004. Pyromex is also actively promoting its technology in North America through its representative, Innovative Logistics Solutions, Inc. (ILS) of Palm Desert, California.

Development of pyrolysis technologies in the U.S. has been considerably more limited, due in part to inexpensive and less restricted landfill options. In California, a number of jurisdictions are researching conversion technologies, including the City of Los Angeles, Alameda Power and Telecom, the Coachella Valley Association of Governments, the County of Santa Barbara, and the County of Los Angeles. While thermochemical technologies may be viable technical alternatives for these jurisdictions, a limiting factor in some of these competitive solicitations is the lack of diversion credits for thermochemical processes.

One potentially important thermochemical process in California is a 50 TPD facility recently constructed by International Energy Solutions (IES) in Romoland, California. This facility is designed for use with a wide range of feedstocks including medical waste, fireworks, MSW, dried sewage sludge, and tires, all of which will be tested as part of their air permitting process. Primary feedstocks planned for actual operation will include pretreated medical waste, electronic waste, fireworks, and tree bark infested with bark beetle. The facility is a modification of a technology originally developed by Balboa Pacific Technology at a small pilot facility in Long Beach, California. Pyromex and ILS has projects for a 400 TPD ASR facility in Anaheim, California, and a 250 TPD green waste facility in Thousand Palms near Palm Springs California.

Several other pyrolysis technologies in North America were identified. North American Power currently has a facility running in Las Vegas, NV.[75] This facility is capable of processing a range of feedstocks including MSW, tires, industrial and medical waste, and liquid sludges. The 1000 pound per hour facility is currently being operated to produce spent carbon. Conrad Industries, Inc. has two pilot scale demonstration plants with capacities of 3.5 and 24 TPD that have been constructed and tested in Chehalis, WA. The testing included a three-year study with the American Plastics Council.[76,77,78] ACM Polyflow Inc. is another company that has demonstrated a 1000 lb. batch process for processing plastics.[79]

Several North American companies have commercialized or are commercializing pyrolysis technologies primarily for wood waste applications, but with potential application to MSW. Ensyn (Boston, MA) has 6 operating pyrolysis units in Ontario and Wisconsin with two others under construction.[80] The units range in size from 40 to 70 TPD but could be made larger. Ensyn, in conjunction with Ivanhoe Energy, is currently constructing a commercial demonstration facility near Bakersfield, California, for the processing of heavy crude oil components into more valuable light components.[81] Dynamotive has a 110 TPD facility nearly constructed and planned for final commissioning in Fall 2004. This facility is located at Erie Flooring and Wood Products in West Lorne, Ontario, and will be used for the processing of wood waste. The bio-oil produced by this facility will be used as fuel for a gas turbine to produce up to 2.5 MW_e.[82,83,84] JF BioEnergy Inc. has applied for a permit to conduct a 3-month pilot project for a 12 TPD facility at a dairy farm in Sumas WA.[85]

Gasification

Gasification, on a commercial scale, has been used in the energy industry for several decades. Its origins date back to the 19th century when coal was used to make town gas (a mixture of hydrogen and carbon monoxide) by passing steam over red-hot coke. The town gas was used to provide lighting throughout cities in Europe and the United States. Early coal gasifiers were similar in design to a coal stove. By 1875, the cyclic carbureted water gas process was developed. With the popularity of gas lighting, heating and cooking growing, gasification progressed quickly into the 1940s. In countries with shortages of petroleum during World War II, wood gasifiers were placed on vehicles to make motor fuels. Some of the early processes included the Winkler fluid bed process, the Lurgi process, and the Koppers-Totzek suspension gasification process. However, after WWII with the advent of the petroleum age and widespread electrification, coal gasification went into a decline. Interest in gasification increased again, during the oil shortage of the 1970s.

Gasification technologies are used commercially in the processing of coal, petroleum and natural gas to produce synthesis gas. Biomass is also gasified, mostly in Europe and East Asia, at a small scale (compared with coal facilities) for heat and power. The use of gasification for these feedstocks has expanded considerably since the early to mid-1970s when almost the entire gasification capacity could be attributed to a Sasol complex in South Africa.[86] Additional Sasol projects beginning in 1977 and 1982 dramatically increased gasification production of synthesis gas. These facilities were primarily the result of South Africa being forced to develop coal resources for energy (including liquid fuels from synthesis gas) because of the nearly worldwide trade embargo due to Apartheid. Gasification is anticipated to expand to 163 facilities by 2006.[87] In the U.S., the Dakota Gasification Co. has been operating a coal gasification facility. The Wabash River Gasification Project in Indiana and the Tampa Electric Polk Power Station IGCC project both utilize coal and pet coke gasification on a large, commercial scale to produce power. For the past 20 years, Eastman Chemical has operated its coal gasification facility in Kingsport, TN, producing syngas from coal, and using it to produce commercial chemicals. Although these processes are not processing MSW, it is expected that the continuing expansion and maturity of gasification technology will provide a foundation that could lead to commercial scale MSW gasification in the U.S. A listing of some of the largest active gasification facilities in the world is provided in Table 3-4.

Table 3-4. Largest Gasification Projects Worldwide[88]

Plant Owner	Location	Technology	MW_{th} SG output	Startup Year	Feedstock	Product
Sasol-II	South Africa	Lurgi dry ash	5,090	1977	Coal	FT liquids
Sasol-III	South Africa	Lurgi dry ash	5,090	1982	Coal	FT liquids
Dakota Gasification	United States	Lurgi dry ash	1,900	1984	Coal&refinery residue	Syngas & CO_2
SARLUX srl	Italy	Texaco	1,217	2001	Petroleum	H_2, power, steam
Shell MDS Sdn. Bhd	Malaysia	Shell	1,032	1993	Natural gas	mid-distillates
Mitteldeutsche Erdöl-Raff. GmbH	Germany	Shell	984	1985	Petroleum/Visbreaker residue	H_2,methanol, power
ISAB Energy	Italy	Texaco	982	2000	Petroleum/Asphalt	Power, steam, H_2
Sasol-I	South Africa	Lurgi dry ash	971	1955	Coal	FT liquids
Global Energy Inc., SVZ plant	Germany	Lurgi dry ash	848	1964	Biomass/MSW	Power, methanol
Millenium (Quantum)	United States	Texaco	727	1979	Natural Gas	Methanol & CO

Due to a number of factors such as very restrictive landfill regulations, high population density, greenhouse gas reduction goals, and lack of domestic energy resources, Europe and Japan have developed gasification processes for MSW. To date, a large number of gasification technologies have been developed and demonstrated on laboratory, pilot plant and fully commercial scales. At least 8 companies have designed MSW gasification facilities that are commercially operating, as shown in Table 3-5, with many of the facilities coming on line in the last 5 years.

Table 3-5. Commercially Active Gasification Facilities using MSW

Location	Company	Began Operation	MSW Capacity*
SVZ, Germany	Envirotherm	2001	275,000 tpy†
Karlsuhe, Germany	Thermoselect/JFE	2001	792 tpd
Ibaraki, Japan	Nippon Steel	1980	500 tpd
Aomori, Japan	Ebara	2001	500 tpd (ASR)
Kawaguchi, Japan	Ebara	2002	475 tpd
Akita, Japan	Nippon Steel	2002	440 tpd
Oita, Japan	Nippon Steel	2003	428 tpd
Chiba, Japan	Thermoselect/JFE	2001	330 tpd
Ibaraki #2, Japan	Nippon Steel	1996	332 tpd
Utashinai City, Japan	Hitachi Metals		300 tpd
Kagawa, Japan	Hitachi Zosen	2004	300 tpd
Nagareyama, Japan	Ebara	2004	229 tpd
Narashino City, Japan	Nippon Steel	2002	222 tpd
Itoshima-Kumiai, Jp	Nippon Steel	2000	220 tpd
Kazusa, Japan	Nippon Steel	2002	220 tpd
Ube City, Japan	Ebara	2002	218 tpd
Sakata, Japan	Ebara	2002	217 tpd
Kagawatobu-Kumiai,Jp	Nippon Steel	1997	216 tpd
Lizuka City, Japan	Nippon Steel	1998	198 tpd
Tajimi City, Japan	Nippon Steel	2003	188 tpd
Chuno Union, Japan	Ebara	2003	186 tpd
Genkai Envir. Union, Jp	Nippon Steel	2003	176 tpd
Iabarki #3, Japan	Nippon Steel	1999	166 tpd
Ishikawa, Japan	Hitachi-Zosen	2003	160 tpd
Kocki West Envir., Jp	Nippon Steel	2002	154 tpd
Nara, Japan	Hitachi-Zosen	2001	150 tpd
Toyokama Union, Jp	Nippon Steel	2003	144 tpd
Mutsu, Japan	Thermoselect/JFE	2003	140 tpd
Minami-Shinshu, Japan	Ebara	2003	155 tpd
Iryu-Kumiai, Japan	Nippon Steel	1997	132 tpd
Maki-machi-kumiai,Jp	Nippon Steel	2002	132 tpd
Kamaishi, Japan	Nippon Steel	1979	110 tpd
Takizawa, Japan	Nippon Steel	2002	110 tpd
Seino Waste, Japan	Nippon Steel	2004	99 tpd
Kameyama, Japan	Nippon Steel	2000	88 tpd
Nagasaki, Japan	Hitachi Zosen	2003	58 tpd
Aalen, Germany	PKA	2001	27,000 tpy
Gifu, Japan	Hitachi Zosen	1998	33 tpd
Bristol, UK	Compact Power	2002	9,000 tpy

* Note that some facilities report capacities in tons per day and some in tons per year. For reference, 100 tpd corresponds to 36,500 tpy for continuous 24 hour/7 days a week operation or approximately or between 31,000 and 33,000 tpy for a more typical operation at 85-90% of capacity.

† Based on Schwager and Whiting, "Progress Towards Commercialising Waste Gasification- A Worldwide Status Report." Presented at 2003 Gasification Technologies Conference, San Francisco. Company literature indicates 450,000 tpy for all solid waste.

Some of the most significant commercialization efforts for the gasification of MSW have taken place in Japan, where currently 75% of the MSW is processed with complete combustion techniques. Nippon Steel of Japan has the largest worldwide capacity for processing MSW using non-combustion thermochemical processes and was the only technology classified to be "fully commercial" for MSW application by Juniper Consultancy as of late 2003 (although the Ebara, Thermoselect/JFE, and Mitsui R21 were also expected to achieve that status in the near future).[89] The Nippon Steel process uses a fixed bed oxygen blown slagging gasifier co-fed with coke. Producer gases are burned in a combustion section with heat recovery for steam or power production. Nearly 20 Nippon Steel plants are operating with several others being built, representing an annual capacity of over 1.2 million tons of MSW. This includes a 500 TPD facility that has been operating since 1980 and a 110 TPD facility that has been operating since 1979.

Ebara/Alstom is another manufacturer of large-scale gasification processes.[90] The Ebara Twin Internally Revolving Fluidized Bed Gasifier (TIFG) combines an air-blown fluidized bed gasifier followed by a cyclonic combustor that melts particulate matter and bed carryover. The technology has been demonstrated on a pilot scale level since the mid-1990s. A 450 TPD facility has been operating in Aomori, Japan since 2000. This facility uses sewage sludge and auto shredder residue as its feedstock. An additional seven plants are in various stages of operation, commissioning, and planning. This includes a plant in Kuala Lumpur, Malaysia, scheduled to be commissioned in May 2006, that will have a capacity of over 1,600 TPD and is expected to be the largest MSW gasification plant in the world. This process is also marketed in Europe by Alstom using the brand name "TwinRec". Other processes that have been demonstrated on a commercial level include the Hitachi Metals plasma arc system. Hitachi has commissioned a plant in Utashinai City, Japan, with a capacity of up to 300 TPD for MSW and several other smaller plants for sewage sludge.

Thermoselect is another one of the more widely applied technologies for MSW processing. This technology was originally developed in Europe, but is also used at several sites in Japan. A semi-commercial, 110 TPD facility was built in Fondotoce, Italy and operated commercially from 1994 to 1999. A facility was also built in Karlsruhe, Germany, in 1999. This facility had problems that led to considerable delays in commissioning. This included the use of an emergency flare resulting in exceedences of cumulative emissions limits until a closed chamber combustion system with exhaust cleaning was installed. The 792 TPD facility was finally commissioned in 2001, and appears to have operated since then. Recent information indicates that the facility is still having financial issues,[91] although representatives from the North American subsidiary of Thermoselect indicate that these issues are being addressed. The delays in the commissioning of Karlsruhe, in combination with other issues, resulted in problems with some other early Thermoselect projects.

The Thermoselect facilities in Japan seem to have proceeded through commissioning more easily, and the technology itself is one of the more widely applied approaches for MSW. A facility in Chiba, Japan, has been operating since 1999 and been operating commercially at a capacity of 330 TPD since 2002. This plant was built by the Kawasaki Steel Corporation, Thermoselect's original Japanese partner. A second plant with a capacity of 140 TPD has been operating in Mutsu, Japan, since 2003. JFE is the company providing the Thermoselect technology for Japan. Thermoselect also has a number of other facilities in various stages of development in Europe, including one in Poland, two in Spain, two in Italy, and three in Ireland.

The development of other gasification systems for MSW is ongoing in Europe but at a considerably lower level than in Japan. Sekundärrohstoff-Verwertungszentrum (SVZ) operates the largest facility in the world and one of the most historically important gasification sites at Schwarze Pumpe in former East Germany. The plant began operation in the 1950s for the production of town gas from coal in the area, but was converted to operate on waste in 1997. The facility can process 450,000 TPY of solid waste and 55,000 TPY of liquid waste.[92] The facility is reportedly processing 276,000 TPY now.[93] The facility produces 75 MW of electricity and 300 TPD of synthesized methanol. SVZ claims to process plastics, waste wood, sewage sludge, domestic garbage (combined or source-separated), and other solid wastes. Liquid and slurry waste oils, solvents, paint sludges, etc., are processed as well. The facility incorporates 10 separate gasifiers including seven Lurgi Dry Ash gasifiers, and one each of Lurgi multi-purpose, British Gas-Lurgi and Noell KRC gasifiers. The Noell KRC gasifier is not currently being marketed for other installations, but it is used in 30 MW entrained flow gasifier processing nylon residues in Middlesbrough, U.K., and a 40,000 TPY facility at Salzgitter, Germany. The Lurgi process is also being used in some other installations for biomass in Germany and the Netherlands, with other potential sites in Europe.

Several other technologies have been demonstrated in Europe on various scales. A 200 TPD circulating fluidized bed gasifier plant was built in Greve, Italy. The plant began operation in 1991 but required remediation to resolve issues with boiler fouling in the late 1990s. Foster Wheeler has been operating a 100,000 TPY gasifier in Lahti, Finland, since 1997. This facility uses approximately 20,000 TPY of MSW and plastics as a feedstock, with the remaining feedstock being primarily wood waste. Foster Wheeler also has a 27,000 TPY gasifier for polyethylene in Varkaus Finland. Emerkem Technologies Inc. built a 25,000 TPY gasifier for plastic waste in Ribesalbes, Spain. PKA currently has a 27,000 TPY facility in Aalen, Germany, that has been operating on a blend of MSW, commercial waste, and sewage sludge since 1999 and a 13,000 TPY unit installed in Freiberg/Saxony, Germany, that processes high aluminium industrial waste in conjunction with an adjacent aluminium melting plant.[94,95] Product en Energie Centrale (PEC) of the Netherlands, which markets the PKA process, has reportedly received approval for a 150,000 TPY facility in Defile, Netherlands, that will have three lines each of four ton per hour capacity. Compact Power has a 9,000 TPY facility that has been operated since 2002 in Bristol, U.K.

One plant that has had operational/financial issues worth discussing is Brightstar Environmental located in Woolongong, Australia. Brightstar Environmental constructed a 55,000 TPY capacity commercial scale demonstration that began commissioning in early 2001.[96,97,98] Apparently, there were problems with the char gasification component of the process and corresponding financial problems with the plant. As a result, the parent company Energy Developments Ltd. announced that it is ceasing to fund further development.

Several gasification technologies have been implemented in North America, although most have focused on feedstocks other than MSW. Future Energy Resource Company (FERCO) is using a two-vessel indirectly heated fluidized bed gasification technology originally developed by the Battelle Columbus Laboratory. With U.S. Department of Energy funding, FERCO operated a wood-fired power station in Burlington, VT, in preparation for installing a gas turbine. Though the gasifier operated successfully, demonstration funding was exhausted before the gas turbine was installed. Manufacturing & Technology Conversion International, Inc. is marketing a system with a multiple resonance-tube pulse combustor in a bubbling fluidized bed. This technology has been tested at a 50 TPD facility in Baltimore, MD, and several paper sludge disposal locations. A 300 TPD coal gasifier is being built in Gillette, WY, and several other facilities are being planned in Germany. Eco Waste Solutions has installed small-scale gasification facilities [ranging in size from 1-25 TPD] at a number of remote locations included Canada, Alaska, Belize, and Hawaii.

Plasma Arc Current Status

Plasma arc technologies are used in the metals production industries, and in fabrication shops where plasma arc metal welding and cutting of metal plate is used extensively. The technology is also used in certain chemical processing applications including the manufacture of acetylene from natural gas. More recently, plasma heating methods are being investigated for use in thermal treatment of foundation soils for stabilization prior to construction.

Plasma heating methods have been applied to hazardous and low-level nuclear waste treatment because volatile and organic material is broken down to small and simple compounds (depends on the waste and gas used in the reactor) that are usually less toxic than that of the feedstock. The inorganic material melts and upon cooling hardens or 'vitrifies' to a glass like solid that typically has very low leachability. Low leachability is an advantage for radioactive solid wastes that must be stored for a very long time when controls against ground water intrusion are not guaranteed.

The technology is used extensively in Japan for melting incinerator ash in order to reduce its leachability. Plasma arc treatment of MSW and non-hazardous industrial wastes is very limited. There are two facilities operating in Japan supplied by Hitachi Metals. Figure 3-5 shows a schematic of the Hitachi Metals plasma gasifier. The largest, at Utashinai City, Japan was completed in 2002 and began commercial operation in 2003. It processes primarily 165 TPD of auto shredder residue but is capable of processing up to 300 TPD of MSW. The plant generates about 7.9 MW_e gross and consumes 3.6 MW_e for the torches and other electric load (46% parasitic load). A smaller facility is located near Mihama and Mikata, Japan and processes about 25 TPD and 4 TPD of MSW and sewage sludge respectively. This facility uses the synthesis gas to produce hot process water.

In California, Chateau Energy Group is refurbishing a power plant near El Centro that had previously used a Lurgi fluidized bed furnace. Chateau Energy is planning to use a plasma arc gasifier for converting tire derived fuel (TDF) and natural gas to generate up to 45 MW_e.

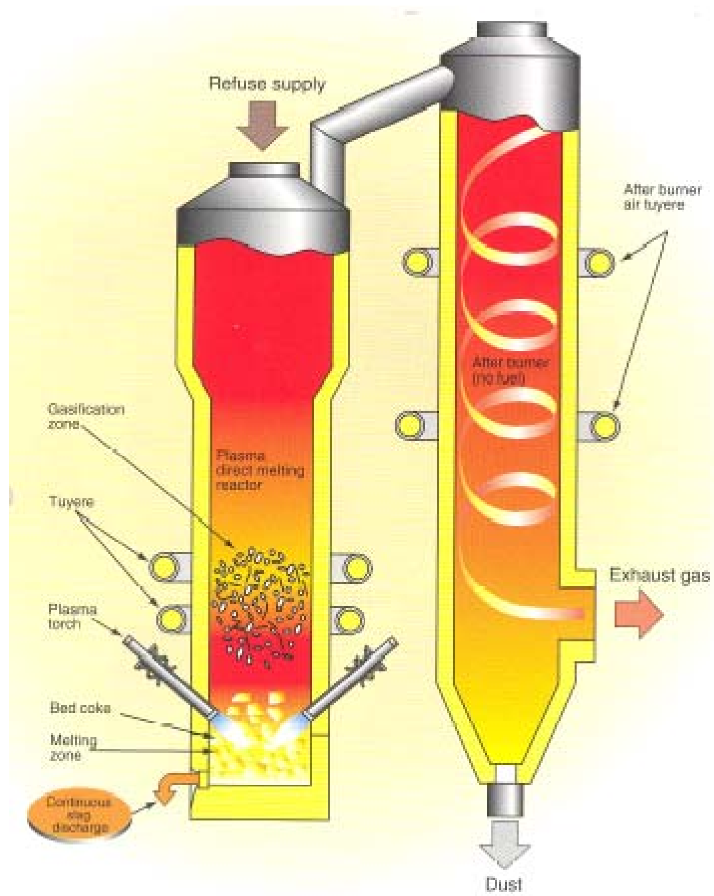

Figure 3-5 Schematic of Hitachi Metals plasma assisted gasifier and gas burner
(Source; Hitachi Metals)

Discussion of Energy Production from Plasma Arc Facilities

Plasma gasification facilities require a large amount electricity to operate the plasma torch. The amount depends on the type of plasma torch, the reactor configuration, energy content of the feedstock, and amount of oxidant (air or oxygen) allowed in the reaction. Plasma arc technology may allow use of gas turbine combined cycle electricity generation technology that has higher efficiency than conventional steam power cycles. However, because of the high energy required by the plasma torch, overall plant electrical efficiencies are comparable to conventional solid waste combustion. Other high temperature slagging gasifier methods (i.e., oxygen blown Lurgi or Emery Energy technologies) feeding gas turbine combined cycle (GTCC) power islands are expected to have similar or better overall electrical production efficiencies compared to plasma arc gasification with GTCC. The efficiency of a system proposed by Emery Energy using an air blown dry ash gasifier feeding reciprocating engine generators with steam bottoming cycle is competitive with the proposed plasma arc systems as well (see Table 3-6).

A recent report on emerging waste disposal systems prepared for the City and County of Honolulu[99] reviewed plasma gasification of solid waste. The report indicates plasma arc gasifiers could be expected to generate 900 kWh of electrical energy per ton of refuse processed. However, only about 200 to 300 kWh per ton of feedstock would be available for export to the grid (about 22% - 33% net of generation). For comparison, the H-Power solid waste-to-energy facility on Oahu, Hawaii, produces net electricity to the grid of 540 to 640 kWh/ton[100] and the

SEMASS facility in Rochester, Massachusetts, exports 610 kWh/ton to the grid.[101] A proposal by Geoplasma LLC for the City and County of Hawaii indicates that a 375 TPD (or 100,000 TPY) facility will generate 10.6 MW_e gross but will consume 4.1 MW_e internally leaving 6.5 MW_e to export to the grid. This is equivalent to 415 kWh/ton of input material. RCL Plasma is another company offering plasma systems for treatment of MSW. Their system pyrolyzes the feedstock (no air or oxygen in the reactor) and the plasma torch requires 600 kWh of electricity per ton of MSW. Depending on the electrical generating technology used in conjunction with the RCL plasma process, the overall efficiency (net electrical energy divided by energy in feedstock) ranges from 0% to about 24%. Information submitted by Emery Energy described a proposed system using a proprietary atmospheric air-blown (dry ash) gasifier operating on RDF (the Emery Energy process does not utilize plasma technology). This system will create a synthesis gas to be fired in reciprocating engine generator sets combined with a heat recovery steam generator for bottoming cycle power production. The system is purported to generate a net of 19.2 MW_e from 650 TPD of mixed MSW (processed to 390 TPD of dRDF). This is equivalent to a net export of energy equal to 736 kWh per ton of mixed MSW (1225 kWh per ton of dRDF).

Table 3-6 shows overall electrical efficiency, net energy per mass of input, and plant parasitic load for several proposed or operating plasma arc treatment facilities, a gasification process, as well as two operating solid waste to energy combustion facilities. The data are compiled from elsewhere in the report and include information reported by companies in their survey response. Plant parasitic load for the plasma arc systems is high, ranging from 39% to 46%. This high parasitic load is indicative of the high electricity requirement of the plasma torches. Overall efficiencies of proposed plasma facilities range from 15% to 35%, which brackets the efficiency for conventional MSW combustion that is approximately 20 %.

Table 3-6 Plant and Technology Overall Efficiency Comparisons

Company	Facilty Information				Overall Electrical Efficiency (%)	Net energy per ton (kWh/ton)	Plant Parasitic Load (%)
	Technology	Status	Location	Capacity (tpd)			
Hitachi Metals	Plasma enhanced gasifier	Operating	Utashinai, Japan	165-300	*	413	46
GlobalPlasma LLC	Plasma enhanced gasifier	Proposed	Honolulu, HI	376	15	415	39
Recovered Energy Inc.	Plasma enhanced gasifier	Proposed	*	3000	29	804	*
RCL	Plasma pyrolyzer	Proposed	*	*	24	712	46
Solena	Plasma enhanced gasifier	Proposed	*	480	35	*	*
Emery Energy	Gasifier w/ recip engine genset and steam cycle	Proposed	*	650	27	736	5
H- Power	Combustion w/ energy recovery	Operating	Honolulu, HI	2000	19	540	13
SEMASS	Combustion w/ energy recovery	Operating	Rochester, MA	2700	22	610	14

Note; Plant parasitic load = (Gross power – Net power)
Generation technology for the Solena and RCL processes were stated or assumed to be gas turbine combined cycle.
Generation technology for the other plasma systems is not determined.
Generation for conventional combustion of MSW is steam Rankine cycle.
* Insufficient information supplied

Catalytic Cracking

Plastic Energy LLC (PE)

Plastic Energy LLC describes its process as catalytic cracking. The process involves melting waste plastic received from MRFs and thermally depolymerizing or cracking the long chain polymers to create a hydrocarbon oil. The oil can be refined with standard technology to create liquid fuels. The waste plastic is melted (using energy supplied by converting some of the product fuels) at a temperature of about 365º F, after which it flows into a reactor (Figure 3-6), is mixed with a metal-silicate catalyst and heated to about 600º F. A volatile crude oil is formed and refined in a conventional distillation process. The final products reportedly are a very low sulfur diesel fuel, a gasoline fraction, and low molecular weight gases (e.g. butane). All of the plastic hydrocarbon content is claimed to exit the process as a usable fuel. Most clean plastic material has very low mineral or ash content so residual material from the process is expected to be very low. Residues, other than spent catalyst, would most likely come from dirt and other impurities incorporated during handling.

There is one existing facility of substantial size located in Zabrze, Poland. Established in 1997, the facility has had two capacity upgrades to the current 145,000 TPY of waste plastic. A smaller sized facility (<3000 TPY) has been operating intermittently in South Korea for several years, primarily as a testing and research facility.

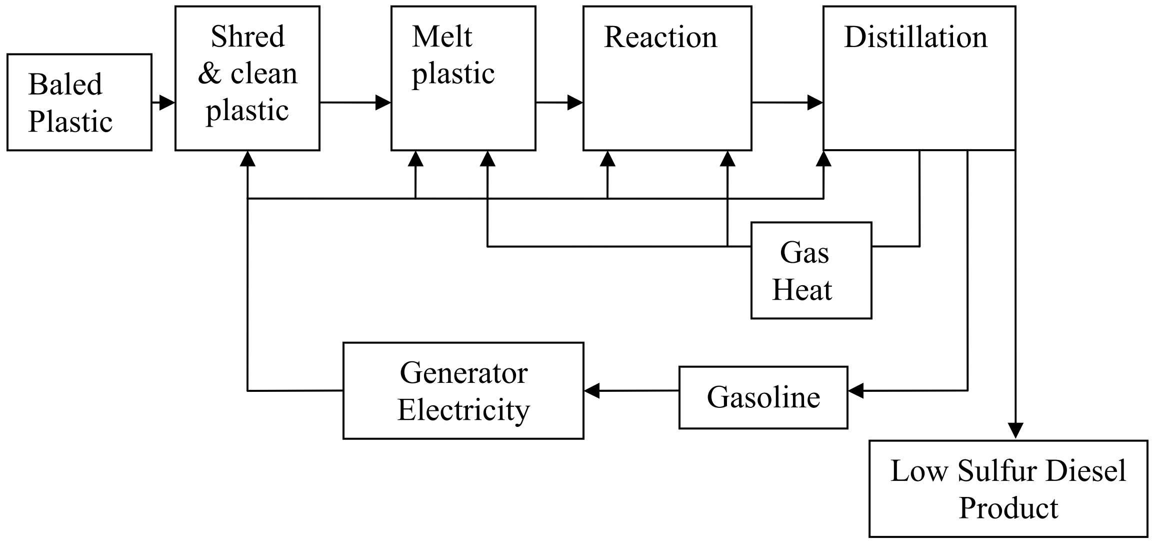

Figure 3 - 6: Schematic of Plastic Energy LLC process.

A proposed facility in Hanford, California, is planning to process only HDPE film plastic, LDPE, polypropylene and polystyrene residual plastic (resin codes 2, 4, 5, and 6). Numbers 1 and 3 plastics (PET and PVC) are to be sorted and removed at the MRF by the waste plastic supplier. Special attention will be paid to remove all PVC plastic from the feed stream. The Hanford facility will be built in two phases, with the first having a 50 TPD capacity, and the second phase providing an additional 50 TPD capacity. Ultimately, the annual capacity is expected to be 33,000 TPY of waste plastic with more than 95% of the feed material being film plastics (#2 and #4 plastics). Plastic films comprise more than 40% of the plastics landfilled in California (see Table 3-7). Catalytic cracking processes like those proposed by Plastic Energy LLC could conceivably divert nearly 44% (1.5 million TPY) of the waste plastic stream in California if only film plastics were converted. In addition, if HDPE containers are targeted as well as an estimated 40% of the remaining plastics waste stream, then it is conceivable that this technology could process as much as 2.6 million tons of waste plastic per year (Table 3-7).[‡]

[‡] Estimate is based on no PET and PVC and about half the remaining plastic types (2,4,5,6,7) acceptable to the Plastic Energy LLC process.

Table 3-7. Waste Plastics Stream and Portion Acceptable to Catalytic Cracking

Plastics component in California landfill stream	Resin Code	Annual Disposal (Million tons/year)[a]	Fraction of disposed plastic stream (%)	Amount acceptable to PE[b] process	
				(%)	(Million tons/year)
Film Plastic	2,4	1.55	43.3	43.3	1.55
Durable Plastic Items	1 to 7	0.72	20.0	10[c]	0.36
HDPE Containers	2	0.32	8.9	8.8[b]	0.32
All other plastic Items	1 to 7	1.00	27.8	9[c]	0.33
Totals		**3.6**	**100**	**~72**	**2.6**

a)Table 1-1 and CIWMB (http://www.ciwmb.ca.gov/WasteChar/Study1999/OverTabl.htm)
b)Plastic Energy LLC
c)Estimated

The Hanford facility will be co-located with a MRF from which some of the plastic feedstock will be provided. However, when the second phase is completed, about 80% of the feed material will be hauled to the site from other MRFs, costing the project about $20 per ton. The feedstock from the Hanford MRF apparently will be made available at no cost to Plastic Energy.

Most of the material will arrive from MRFs in bales. The bales will be fed directly into a shredder that will cut the material to particles of 3" or smaller. The shredded material is passed over an air-blown vibrating screen to separate some dirt and loose contaminating items. The material then goes into a mechanically stirred water flotation tank. The heavier fraction, including PVC, is separated by density. The separated material will be centrifugally dried and introduced into the melting process. The low levels of moisture in the plastic feed are reportedly not a problem in the melting process. The capital and operating costs of this separating facility have not be presented, and are unknown.

The patent describes the catalyst as being comprised of silicates of iron (Fe^{3+}), cobalt (Co^{2+}), nickel (Ni^{2+}), manganese (Mn^{2+}), chromium (Cr^{3+}), copper (Cu^{2+}), zinc (Zn^{2+}), and cadmium (Cd^{2+}). Catalyst is applied at a rate of 5%-10% by weight of the feedstock material. It is reused multiple times but eventually will lose effectiveness and require replacement. Plastic Energy estimates approximately 1100 lbs per month of catalyst will need to be disposed or returned to the supplier. Plastic Energy claims the used catalyst is not a hazardous waste, though test reports have not been provided

A small amount of make-up water is required for the up-front cleaning/separation module though the amount was not specified.

All of the polymer material present in the waste plastic should end up in one of three product streams: low sulfur diesel, gasoline, and light hydrocarbon gases. Approximately 85% of the input mass exits as the diesel fuel product. The diesel is expected to have very low sulfur content of <5 ppm. Regulations in California will require diesel fuel to have sulfur content of 15 ppm or less by 2006. Plastic Energy reports that the diesel product has a cetane value that consistently exceeds 65 and averages 80. The gasoline and light gases are estimated at 14% and 1% of the input mass respectively. Using standard petroleum diesel and gasoline densities, total liquid product is estimated to be about 287 gallons per ton of feedstock (see Table 3-8).

The process is expected to be powered by burning the gasoline and light hydrocarbon fractions in a gas turbine-generator set and a gas heater. The simple-cycle gas turbine will have a capacity of approximately 1.2 MW_e and will supply the electricity for the MRF and conversion facility (about 150 kW for the up-front MRF and 800 kW for the conversion process). No off-site electrical sales are planned.[§] Approximately 90% of required process heat will come from the gas turbine exhaust and about 10% from an auxiliary gas heater burning the gas product from the process. Natural gas will be available as back-up and as a start-up fuel.

Table 3-8. Mass and Energy Distribution in Products for the Hanford Facility (per ton input feed).

Product	Product as a fraction of feedstock (mass %)	Product Liquid Volume (gals./ton feedstock)+	Btu/gal	MMBtu/ (ton of feedstock)	Energy Flow-24 hr/day operation (MW)	
					50 ton/day input	100 ton/day input
Diesel	85	242	137,860	33.40	20.3	40.5
Gasoline	14*	45	125,000	5.62	3.3	6.7
Light Hydrocarbons	1*	(vapor)		0.4*	0.2	0.5
Totals	**100**	**287**		**~39.4**	**23.8**	**47.7**
Feedstock						
Film Plastic				39.40	23.8	47.7
Estimated Energy Efficiency (%)‡				85		

* Estimated
+ Used densities of 7.02 and 6.23 (lbs./gal.) for diesel and gasoline respectively
‡ Assumes gasoline and light hydrocarbon energy used for process energy

Air emissions would be typical of those for a gas turbine fueled by gasoline and a natural gas heater or boiler. Selective catalytic reduction (SCR) using ammonia injection for NO_x control from the gas turbine will be included. The emission threshold limits and estimated emission levels are shown in Table 3-9.

Table 3-9. Estimated Air Emissions and Threshold Limits for the Hanford Facility

Emission	Feedstock Input Rate		Thresholds (lbs/yr)
	16,500 tons/yr	33,000 tons/yr	
	Estimated Emissions (lbs/yr)		
NOx:	2,192	4,384	20,000
VOC	2,706	5,412	20,000
CO	10,220	20,440	30,000
PM-10			29,200
SOx	-	-	54,750
NH_3			10% slip

[§] For the facility in Poland, the economics are such that crude oil product is sold and electricity to operate the facility is purchased.

Solid residues will consist of dirt and paper labels separated from the shredded plastic before being sent to the reactor as well as spent catalyst. The inert material and paper separated in the plastics cleaning step would probably be landfilled. The amount of this residue is likely to be very low, on the order of 1-5% by mass of input material.

Plastic Energy indicates that the reason for specifying no PVC in the delivered feedstock is because chlorine will lead to unacceptable corrosion rates in the reactor and distiller and would need to be removed from the product diesel or gasoline before selling or using. It is easier and less expensive to remove PVC plastics from the feedstock.

3.2 Biochemical Processes

3.2.1 Overview

Biochemical processes include composting (aerobic digestion), anaerobic digestion (digestion in the absence of air/oxygen) and fermentation. These processes can convert a portion of the biogenic component of solid waste. The fossil derived carbon containing portion of the mixed waste stream like plastics is generally not biodegradable[**]. Landfill gas from in-place MSW is the product of anaerobic digestion.

Applying biochemical processing to MSW before it is landfilled can reduce both the volume of landfilled material and the production of leachate. Typical products from biochemical processes include soil amendments, fertilizer, biogas (methane and carbon dioxide), andethanol. These processes are being used to convert or stabilize MSW throughout the world. Other than one full-scale landfill bioreactor demonstration project (Yolo County Landfill Bioreactor), there are no existing biochemical processing facilities using anaerobic digestion or fermentation methods in the state.

The composting of green waste consumes about 10% of the MSW generated in California.[††] Composting is a process of aerobic digestion in which organic material is decomposed by aerobic bacteria to stabilize and reduce the volume of the feedstock and produce useful materials, such as mulch, soil amendments, and land applied fertilizers. The emerging organic farming industry in California represents an increasing market for composted material.[102]

3.2.2 Fermentation

Fermentation Overview

Fermentation is an anaerobic process and is generally employed industrially to produce fuel liquids such as ethanol and other chemicals. Although fermentation and anaerobic digestion are commonly classified separately, both are fermentation methods designed to produce different products. Cellulosic feedstocks, including the majority of the organic fraction of MSW, need pretreatment (acid, enzymatic, or hydrothermal hydrolysis) to depolymerize cellulose and hemicellulose to monomers used by the yeast and bacteria for the fermentation process. Lignin in

[**] There are bacteria that degrade liquid petroleum components. Some plastics made from biomass feedstocks are biodegradable. The amount of these plastics in the disposed waste stream is essentially nil.
[††] Assumes 8 million TPY are diverted from the estimated 76 million TPY of generated solid waste.

biomass is refractory to fermentation and as a byproduct is typically considered for use as boiler fuel or as a feedstock for thermochemical conversion to other fuels and products.

Fermentation of biomass material into ethanol is fully commercial for sugar and starch based feedstocks such as corn and sugar cane but it is not yet commercial for cellulosic biomass because of the high expense or low sugar yields from the hydrolysis process and is the subject of intense research. The biodegradable fraction of most MSW streams contains significant amounts of cellulosic biomass (for example, paper, woody residues, yard wastes, and some food waste) that are more difficult than starch and sugars to convert to ethanol. Systems that propose to use post-recycled MSW for fermentation feedstock rely on the expectation that the feed material has a tipping fee associated with it.

Fermentation Process Description

Hydrolysis (Pretreatment before Fermentation)

Cellulosic feedstocks require pretreatment to separate the cellulose and hemicellulose from the cellulo-lignin matrix and depolymerize the compounds into simple sugars, to allow fermentation to proceed and produce ethanol. Hydrolysis methods include the use of acid solutions, biologically produced enzymes, or hydrothermal means. The three strategies can be employed separately or in combination. The USDA/USDOE Roadmap for Biomass Technologies lists physical, chemical, and biological (enzymatic) pre-treatment and hydrolysis processes as key areas requiring technical advances for sustainable and economic biomass conversion.[103]

Cellulosic ethanol processes can be differentiated primarily by the hydrolysis method. Methods that have been investigated the most are acid processes, enzymatic hydrolysis, and steam explosion. Acid processes are technologically mature, but enzymatic processes are projected to have a significant cost advantage once improved.[104] Steam explosion requires less initial size reduction of the feedstock, but yields less pentose, which are sugars that contain five carbon atoms, and releases more material that can inhibit the fermentation process.

The ideal pretreatment process would have these attributes[105]

- Produce reactive fiber
- Yield pentoses in non-degraded form
- Yield no fermentation inhibitors
- Require little or no size reduction
- Require moderate size and cost reactors
- Produce no solid residues
- Simple process
- Effective with low moisture feedstocks

In dilute-acid hydrolysis, biomass that has been chopped or pulverized is treated in a dilute or concentrated acid medium. Most current dilute acid hydrolysis processes utilize two stages, one optimized for the hemicellulose component and the other a more severe stage for the cellulose fraction (Figure 3-7).[106] Cellulose is more difficult to hydrolyze because much of it is bound up in the ligno-cellulose structural matrix. Process temperatures are typically near 464° F (which by itself is a form of hydrothermal hydrolysis). The use of dilute acid hydrolysis is the oldest technology for converting biomass into its component sugars for subsequent fermentation to ethanol.

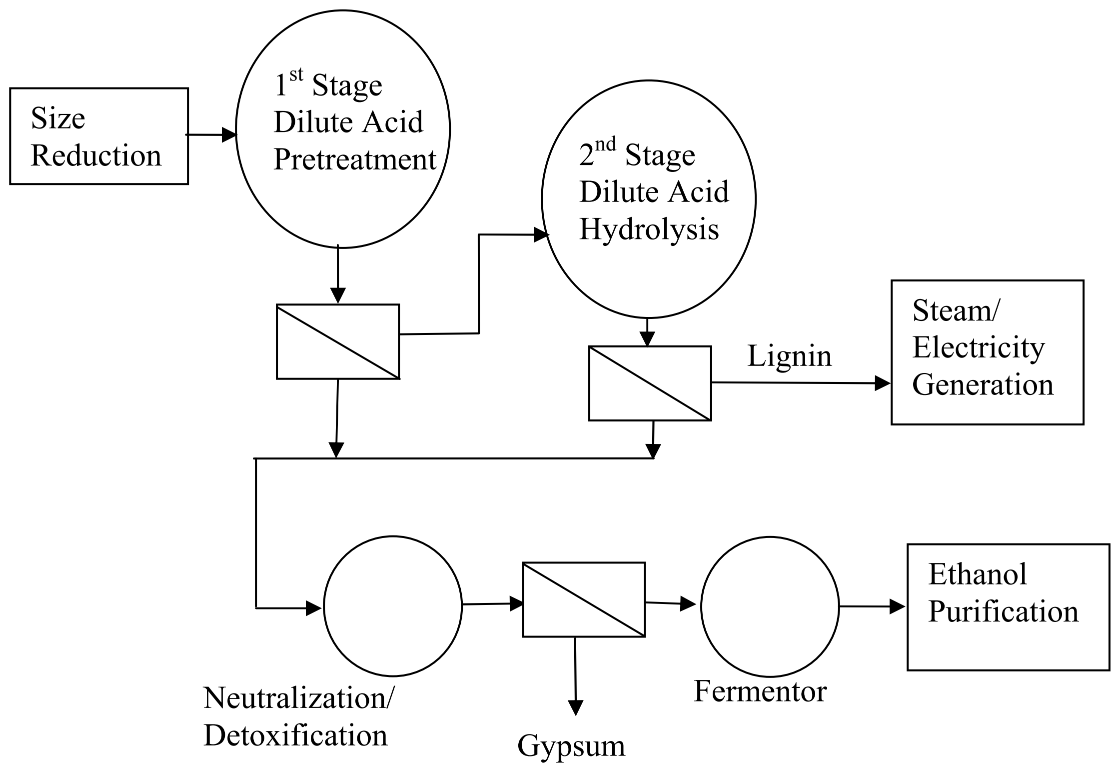

Fig. 3-7: Schematic of typical two-stage dilute acid hydrolysis fermentation.

Concentrated-acid hydrolysis uses concentrated sulfuric acid to decrystallize the cellulose followed by dilute acid hydrolysis to sugars with near theoretical yields. Critical operations include separation of sugar from acid and acid recovery with re-concentration.[107] The concentrated acid process includes a step to separate the acid-sugar stream through a separation column that yields a 25% concentrated acid stream and a 12 to 15% concentrated sugar stream (Figure 3-8). The sugar recovery can be up to 95%, whereas the acid recovery is typically about 98%. The recovered acid is concentrated and reused. The sugar stream, which contains no more than 1% acid, can then be fermented. Concentrated acid hydrolysis generally releases more compounds that inhibit fermentation.

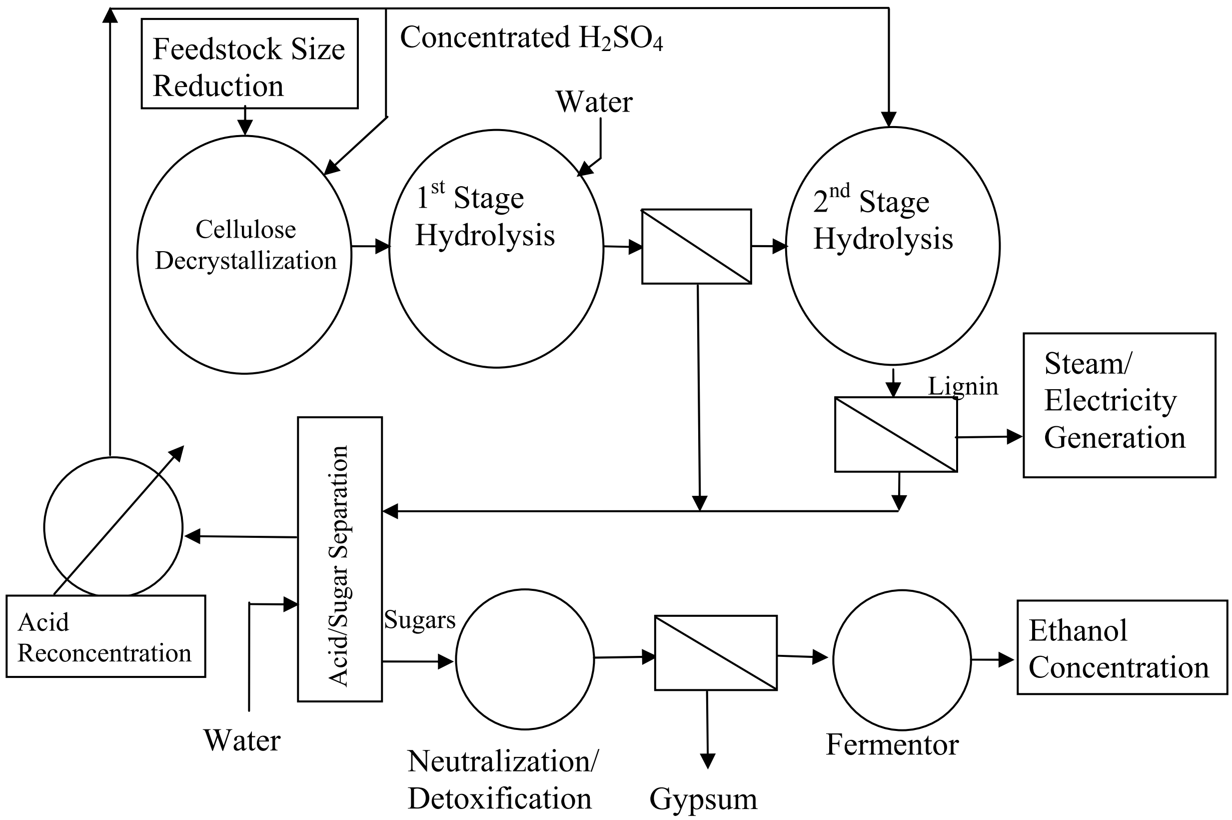

Fig. 3-8: Schematic of concentrated acid hydrolysis fermentation. (Adapted from http://www.ott.doe.gov/biofuels/concentrated.html)

Ethanol production using enzymatic hydrolysis uses enzymes derived from common fungi. Research has been directed at improving cost and performance of cellulase[‡‡] and is ongoing worldwide at both public and private research institutions. Improvements in enzymatic hydrolysis are expected which will make ethanol production from cellulosic biomass competitive with that produced by the starch/sugar platform.

Hydrothermal hydrolysis processes include the relatively simple hot-compressed water (HCW), as well as steam explosion and supercritical water techniques. The ionic product of water changes with the temperature, and reaches the maximum value at around 480°F. Therefore, HCW conducted at around 480 °F is considered optimal for this method of hydrolysis. Steam explosion involves pressurizing the biomass with steam for a period followed by rapid depressurization. The result is a lignocellulosic mulch with much more of the cellulose exposed and more accessible to hydrolysis in neutral and/or acidic or alkali solvents.[108]

Ethanol Production

Fermentation by yeast to ethanol product is well established and commercial for sugar and starch based feedstocks. Cellulosic feedstock material must be hydrolyzed to break the cellulose and hemicellulose polymers into simple sugars that are fermentable by yeasts. As with anaerobic digestion to biogas, lignin cannot be hydrolyzed or fermented.

[‡‡] Microorganisms that produce enzymes that can effectively hydrolyze cellulose are called cellulases.

Once the cellulose has been hydrolyzed, and conditions made favorable (e.g., pH and temperature adjusted), ethanol is produced from microbial fermentation. A variety of microorganisms, generally bacteria, yeast, or fungi, ferment carbohydrates to ethanol under anaerobic conditions. Ethanol inhibits microbial growth, essentially halting the process when ethanol concentration is near 12%. Ethanol must be separated from the fermentation broth and concentrated by conventional distillation technology and dehydrated to yield fuel grade ethanol. The remaining liquid broth is recycled or sent to a wastewater treatment facility for appropriate management.

3.2.3 Anaerobic Digestion (AD)

Anaerobic Digestion Overview

Biodegradation of organic material occurs in nature principally through the action of aerobic microorganisms. Ultimately, partial oxidation of the ingested organic material is the result yielding waste carbon dioxide and water and undigested residue. Anaerobic bacteria will also degrade biogenic organic matter in the absence of oxygen with ultimate products being non-reactive residues, waste carbon dioxide and methane. These bacteria naturally occur in the environment in anaerobic "niches" such as marshes, sediments, wetlands, and the digestive tracts of ruminants and certain species of insects.

AD is a fermentation technique typically employed in many wastewater treatment facilities for sludge degradation and stabilization but also the principal process occurring in landfills. Large dairies and swine farms in the U.S. are turning to the use of AD primarily as a means to mitigate the environmental impacts of manure lagoons with some capture of methane for energy production. Many household scale digesters are employed in rural China and India for waste treatment and gas production. Approximately 5 million households in China use anaerobic digesters. The digesters produce biogas that is used as an energy source by the households, and produce fertilizer that is used in agricultural production.[109] Europe, especially Denmark, has developed large-scale centralized systems for solid waste stabilization and energy generation as a by-product.

Anaerobic Digestion Process Description

Anaerobic digestion of lignocellulosic waste occurs in a 3-step process. These steps are hydrolysis, acetogenesis, and methanogenesis. The molecular structure of the biodegradable portion of the waste that contains proteins and carbohydrates is first broken down through hydrolysis. The lipids are converted to volatile fatty acids and amino acids. Carbohydrates and proteins are hydrolyzed to sugars and amino acids. In acetogenesis, acid forming bacteria use these byproducts to generate intermediary products such as propionate and butyrate. Further microbial action results in the degradation of these intermediary products into hydrogen and acetate. Methanogenic bacteria consume the hydrogen and acetate to produce methane and carbon dioxide. A schematic of these pathways is given in Figure 3-

9.

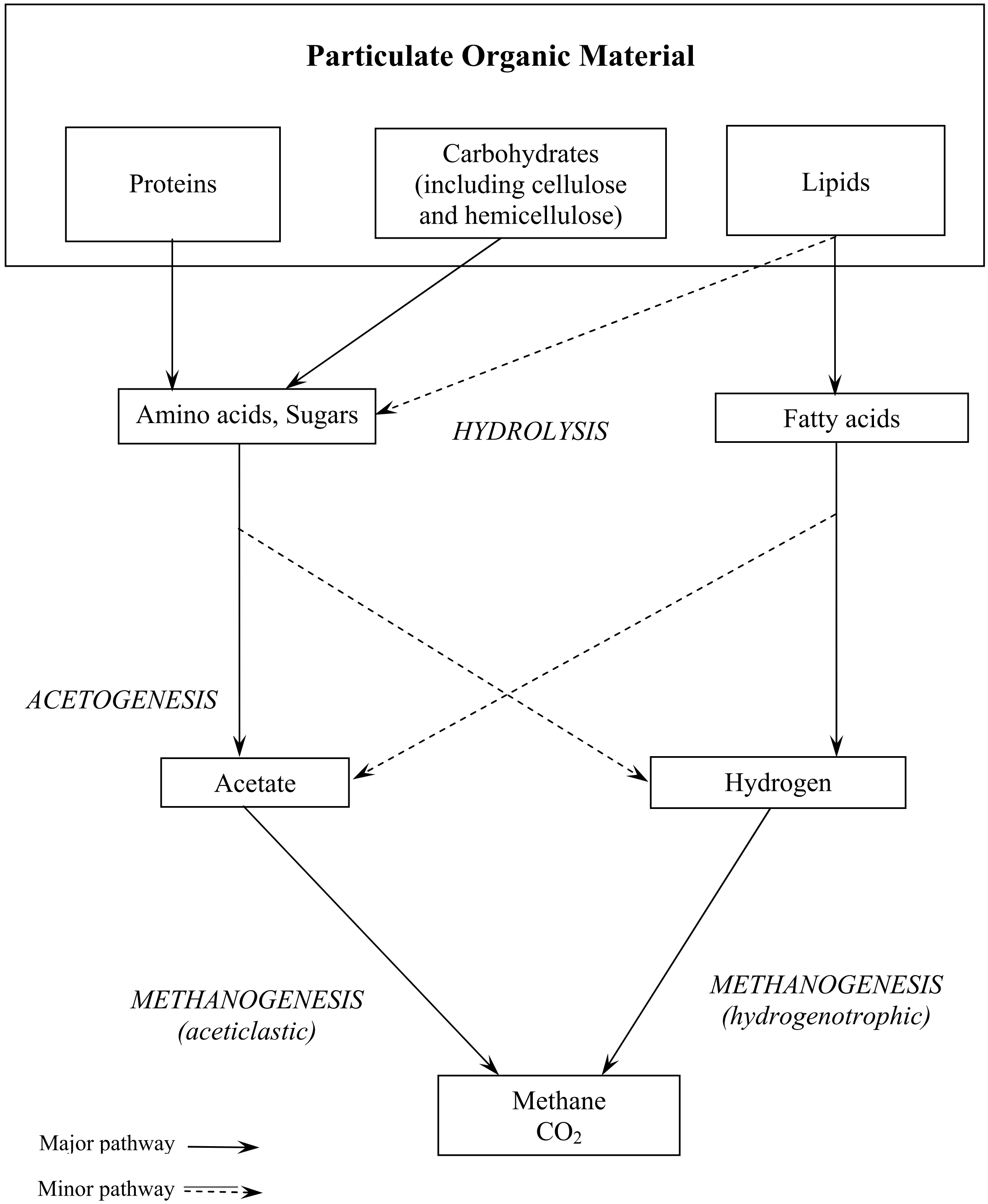

Fig. 3-9 Anaerobic Digestion Pathways[110] of Presorted MSW, ignoring Residues.

Anaerobic digestion operates without free oxygen and produces biogas. Biogas consists of mostly methane and carbon dioxide but also has impurities such as moisture, H_2S, and particulate matter. Anaerobic digestion requires attention to the nutritional demands of the bacteria degrading the waste substrates. The carbon/nitrogen (C/N) ratio of the feedstock is especially important. Biogas can be used as fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, and the manufacturing of chemicals (with emissions and impacts commensurate with those from natural gas feedstocks).

Anaerobic digester systems can be categorized according to whether the system uses a single reactor stage or multiple reactors. In single stage systems, the essential reactions (hydrolysis/acidification, acetogenesis, and methanogenesis – Figure 3-9) occur simultaneously in a single vessel. With 2-stage or multi-stage reactors, the reactions take place sequentially in at least two reactors.

Single stage systems are generally simpler to operate, have fewer components for maintenance or failure, and have smaller capital costs. Multistage systems offer the potential to increase the rate of methane production and the amount of overall biodegradation of the feedstock by separating and optimizing the different steps of the biochemical process. Multi-stage reactors separate the hydrolysis/acidification from the acetogenesis and methanogenesis stages.

Another important classification or design parameter is solids concentration in the reactor. Solids (or total solids, TS) are usually expressed as a fraction of the total mass of the prepared reactor feedstock (typically as a percentage by weight). The amount of moisture, by definition, is 100 – TS (%). The classification scheme for solids content is usually described as being either high solids (HS) or low solids (LS). HS systems are also called dry systems and LS may be referred to as wet. A prepared feedstock stream with TS less than 15% is considered low solids (wet) and feedstocks with TS greater than 15% are considered high solids (dry). In HS systems, solids content is usually kept in the range of 20-40% TS (dilution with process water to desirable solids content is typically done in feedstock preparation stages).

Single-Stage Systems (Low Solids)

Single-stage wet (LS) anaerobic digestion systems are attractive because of their similarity to anaerobic stabilization of wastewater at wastewater treatment plants (WWTPs). The solid wastes are pulped and slurried to less than 15% TS with water to a consistency not unlike that of biosolids before stabilization in WWTPs. Though conceptually simple, there are certain drawbacks to single stage wet systems including extensive pretreatment, higher water consumption and potentially high energy requirements to operate the system.

An early full-scale single-stage, LS plant for treating MSW was built in Waasa, Finland, in 1989 (Figure 3-10).[111] The feedstock is homogenized and diluted using water to obtain the required solids content in a pulping step. Hydrolysis of the carbohydrate substrate will begin in the pulping operation, although the majority of the hydrolysis phase takes place in the reactor tank.

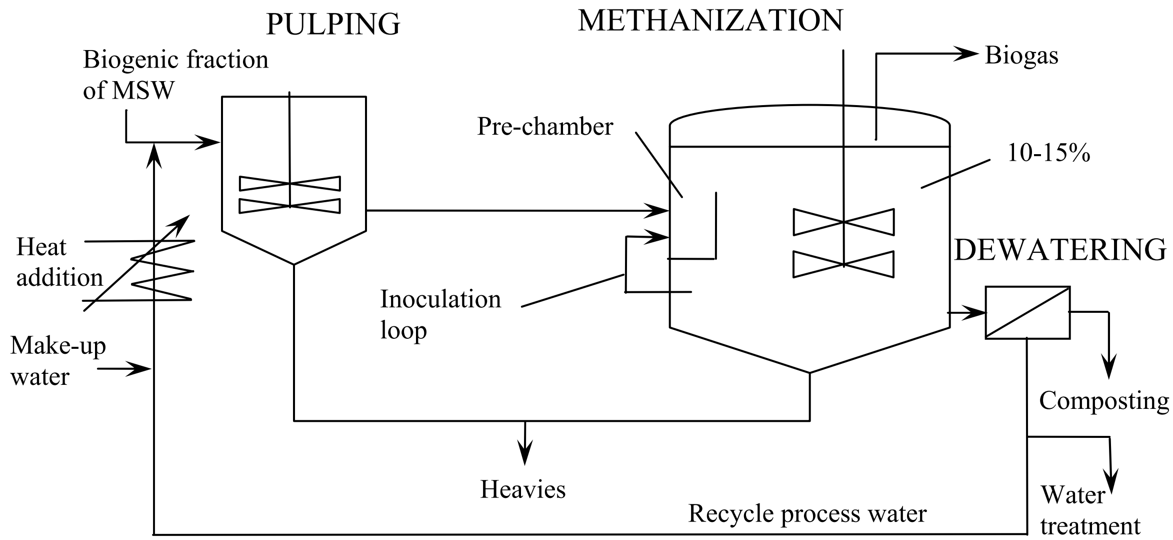

Fig. 3-10. Schematic of a Typical Single-Stage LS Digester *
***[Adapted from Mata-Alvarez, J. (2003)]**

The slurry is pumped into a large complete mix reactor (also called a continuously stirred tank reactor; CSTR) where active mixing keeps solids in suspension.

A true CSTR system which has continuous inflow and outflow will experience something called "short-circuiting" which is the passage of a portion of the feed through the reactor with a shorter retention time than that for the average bulk material. Short-circuiting diminishes biogas yield and emits a less biologically stabilized effluent. To counteract short-circuiting in complete mix reactors, some systems use a pre-chamber where the feedstock is inoculated with organisms from the reactor vessel(Figure 3-10). The material in the pre-chamber moves in plug or "piston" flow, which takes several days to go from the point of injection to where it joins the complete mix portion of the reactor, thus ensuring all material entering the process has a guaranteed minimum retention time. The process can be operated at both thermophilic (approximately130ºF) and mesophilic (approximately 95ºF) temperatures. The plant in Waasa, Finland has both types running in parallel with the thermophilic process having a retention time of 10 days and the mesophilic process having a retention time of 20 days).

The pretreatment required to obtain adequate slurry quality while removing coarse or heavy contaminants is complex and inevitably incur a 15%-25% loss of volatile solids.[112] Mechanical mixing and/or injection of a portion of the biogas into the bottom of the reactor tank is used to keep the material continuously stirred and homogenous as possible. However, energy for vigorous mixing is substantial, so practical systems require means to remove heavy material that doesn't remain suspended as well as a floating scum layer which can build up to several feet thick.

Single-Stage Systems (High Solids)

In dry, or HS, systems, the fermenting mass is kept at a solids content of 20%-40% TS (equivalent to 60%-80% moisture). The physical characteristics of material at the higher solids content require different approaches to handling and pre-treatment (i.e., conveyor belts, screws, and special pumps for the highly viscous streams). As single stage wet systems were based on the well established anaerobic digestion of waste waters, research in the 1980s indicated the biogas yield and production rate were as high or greater in systems that kept the waste feedstocks in their original solid state (i.e., not slurried with water).[113] The challenge of these systems is handling, mixing, and pumping of the high solids streams rather than maintaining the biochemical reactions.

Although some of the handling systems may be more expensive than those for wet systems (such as high solids pumps), the HS systems are more robust and flexible regarding acceptance of rocks, glass, metals, plastics, and wood pieces in the reactor. These materials are not biodegradable and won't contribute to biogas production but they generally can pass through the reactor without affecting conversion of the biomass components. The only pretreatment required is removal of the larger pieces (greater than 2 inches), and minimal dilution with water to keep solids content in the desired range.

Because of their high viscosity, material in HS reactors moves via "plug flow" with no mixing occurring. This presents the problem of inoculating newly injected feedstock with a portion of the fermenting mass. At least three commercial-scale designs have been developed which adequately inoculates the feedstock by mixing a portion of the digested material or recirculating biogas (Figure 3-11).

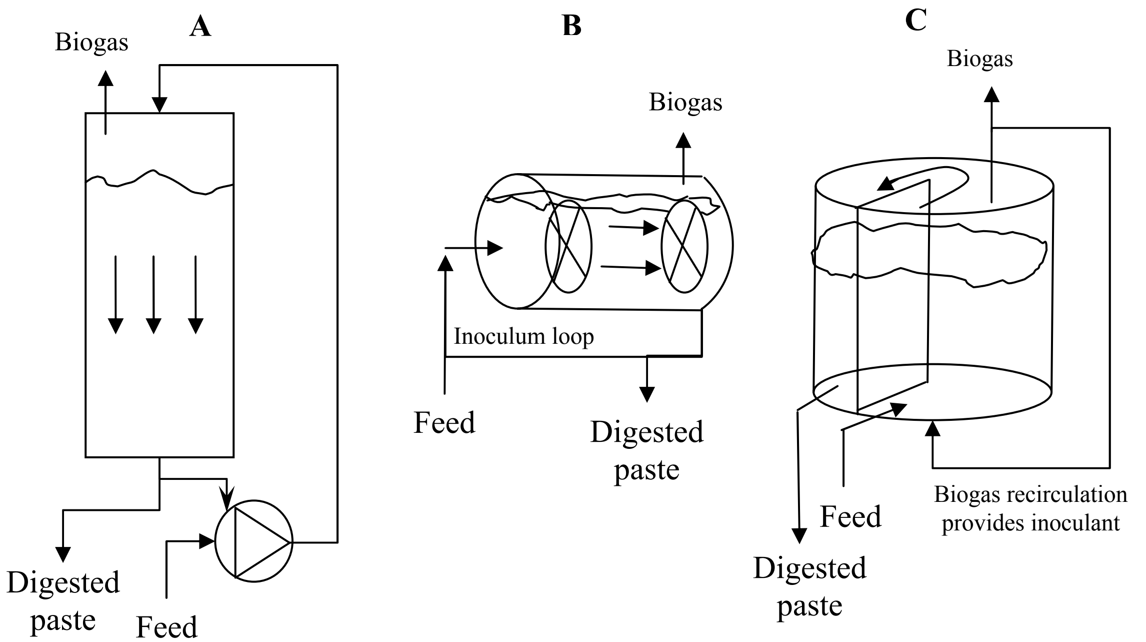

Fig. 3-11. High Solids Single Stage Digester Designs (A – Dranco, B – Kompogas, C-Valorga) Adapted from Mata-Alvarez, J. (2003)

The Dranco process, diagrammed in Figure 3-11 (A), mixes some digested paste with the incoming feed and pumps the mixture to the top of the reactor vessel. Fermenting material flows downward, eventually exiting at the bottom with biogas being recovered through the top. The Kompogas reactor also mixes a portion of the digestate with the incoming feed. This process is a horizontal plug flow reactor with the material moving from the input end to the opposite end. The horizontal reactor has a set of internal impellers that slowly move the material along (some amount of mixing is provided as well). The Kompogas system requires a careful adjustment of TS to about 23%.[114] If TS is too low, heavy materials tend to accumulate on the bottom and do not exit the system, while higher TS values become too difficult to move. The third concept in Figure 3-11 was adopted by the Valorga process. This reactor consists of a vertical cylinder with a vertical inner wall mounted along a diameter of the reactor but only extending about 2/3 of the way across to the opposite side. Material enters at the bottom on one side of the inner wall and must flow a circular path to pass to the other side-wall before it exits.[115] Biogas is periodically re-injected in the base of the reactor (on either side of the dividing wall) providing an inoculum and effecting some vertical mixing and solids suspension with no mechanical mixing devices inside the digester.

Two-Stage Systems

Multi-stage systems are designed to take advantage of the fact that different portions of the overall biochemical process have different optimal conditions. By optimizing the secondary reactions, the overall rate can be increased. Typically, two-stage processes attempt to optimized the hydrolysis and acidification reactions in the first stage where the rate is limited by hydrolysis of cellulose. The second stage is optimized for acetogenesis and methanogenesis where the rate in this stage is limited by microbial growth rate. With multi-staging, it is possible to increase hydrolysis rate by applying a microaerophilic process. This process uses minimal air to allow some aerobic organisms to break down some of the lignin that makes more cellulose available for hydrolysis. The air would inhibit the methanogenic organisms if they were present as they would be in a single stage reactor. Figure 3-12 depicts a basic two-stage AD system with hydrolysis occurring in the high-solids first stage and methanogenesis occurring in the low-solids second stage.

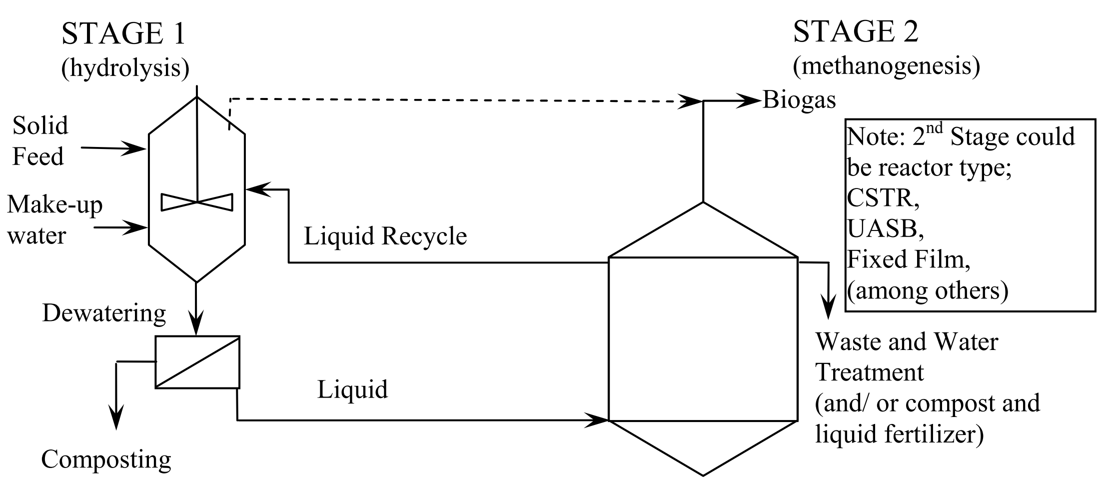

Fig. 3-12 Simple Schematic of Two-Stage Anaerobic Digestion System (high solids 1st stage, low solids 2nd stage) Adapted from Mata-Alvarez, J. (2003)

As mentioned earlier, in Europe there are approximately seven AD plants using two-stage designs and 79 single-stage plants. It was expected that more of the multi-stage systems would be in operation by now, but the degree of increased yield and rates demonstrated in lab scale multi-stage systems have not been duplicated in the commercial units.

Performance of Some Commercial and Practical Pilot Scale Facilities

Table 3-10 lists some methane production values reported on a per VS basis for some commercial facilities in Europe and some pilot scale experiments. Some of the feedstocks are characterized.

These facilities are nominally operated at thermophilic temperature (around 130º F) and retention times of about 15 days.

The SEBAC experiments were conducted for 21 and 42 days with batch reactors at 120º F. This temperature was used because it "represented the natural temperature expected to result from metabolic heat as determined by systems calculations."[116]

Methane production from the DRANCO plants cited in the literature seems respectable and reflects the fact the feedstocks are generally source separated and the food and green wastes are targeted for the anaerobic digesters.

Table 3-10 Performance Data of Some Commercial and Pilot Anaerobic Digestion Facilities

Plant (or reference)	Feedstock	TS (%)	VS/TS (%)	VS (g/g input)	VS reduction (%)	CH_4 production (l/g VS)	CH_4 production (g /g VS)	CH_4 Energy (MJ/kg VS)	CH_4 Energy (MJ/kg Input)
Dranco, Salzberg (De Baere, 2000)	80%Kitchen 20% Garden wastes	31	70	0.217	70	0.34	0.24	13.6	2.9
Dranco, Bassum (De Baere, 2000)	"Grey" waste	57	51	0.2907	60	0.28	0.20	11.0	3.2
Dranco, Brecht (De Baere, 2000)	15% Kitchen 75% Garden 10% Paper wastes	40	55	0.22	52	0.26	0.18	10.2	2.2
Venice (Cecchi et al., 1989)						0.25	0.18	10.1	
France/Valorga (begouen et al., 1988)						0.22	0.16	8.7	
Marseille (Marty et al., 1986)		35				0.20	0.15	8.1	
SEBAC pilot 42 days (O'Keefe et al., 1993)	60% paper, 6% yard waste	71	81	0.5751	49.7	0.19	0.14	7.5	4.3
SEBAC pilot 21 days (O'Keefe et al., 1993)	95% paper, 2% yard waste	65.6	92.5	0.6068	40.6	0.19	0.14	7.5	4.6
SEBAC pilot 21 days (O'Keefe et al., 1993)	60% paper, 6% yard waste	71	81	0.5751	36.0	0.16	0.11	6.3	3.6
Venice (Cecchi et al., 1989)						0.16	0.11	6.3	

Biochemical Processes Current Status

Anaerobic Digestion

Anaerobic digestion systems using solid waste feedstocks are more widely utilized in Europe. European Community policies have developed to minimize the amount of material being landfilled. These policies are driven by several factors including limited space for new landfills, and the needs for methane emission reductions and increased renewable energy production because of Kyoto Protocol requirements. Examples of policies implemented to reduce material flow to landfill in Europe include Germany's Extended Producer Responsibility (EPR) approach that requires manufacturers to be responsible for recovery of packaging material, and restrictions on the amount of biodegradable material that can be disposed in landfills

Anaerobic digestion and aerobic composting of kitchen, food processor, and garden wastes is well established in Europe. To improve the quality of feedstocks used in AD and composting operations, source separation of household and commercial food and garden wastes is utilized extensively. At least 11 EU countries have implemented or are about to implement source separation for food and green wastes[117]. In Switzerland for example, approximately 220 lb per person per year of source separated food and green waste is collected. About 12% of the material is stabilized by AD facilities, and the balance is composted.[118] Germany has more than 500 facilities that treat more than 8 million TPY of green and food wastes in biochemical treatment facilities with the majority being aerobic compost facilities.[119]

A review of the AD of organic waste industry in Europe was done in 2000 and updated in 2003.[120,121] In the 2003 update, 86 AD facilities were identified as either operating or to be under construction by 2004 with capacity greater than 3000 metric tons per year and with at least 10% of the treated feedstock from municipal or commercial organic waste. Many of these facilities will co-digest animal wastes and municipal waste water sludges. In Spain, the 13 large capacity plants, which average 70,000 TPY, will be anaerobically treating nearly 7% of the biodegradable MSW by the end of 2004.[122] For all of Europe, the installed capacity in 2000 was 1.1 million TPY and was projected to increase to 2.8 million TPY in 2004, an increase of approximately 250% in four years. Figure 3-13 shows installed capacity of MSW AD facilities between 1990 and 2004. Figure 3-14 shows how the capacity is distributed between single and two stage systems. Single-stage anaerobic digesters account for approximately 92% of the installed AD capacity in Europe.

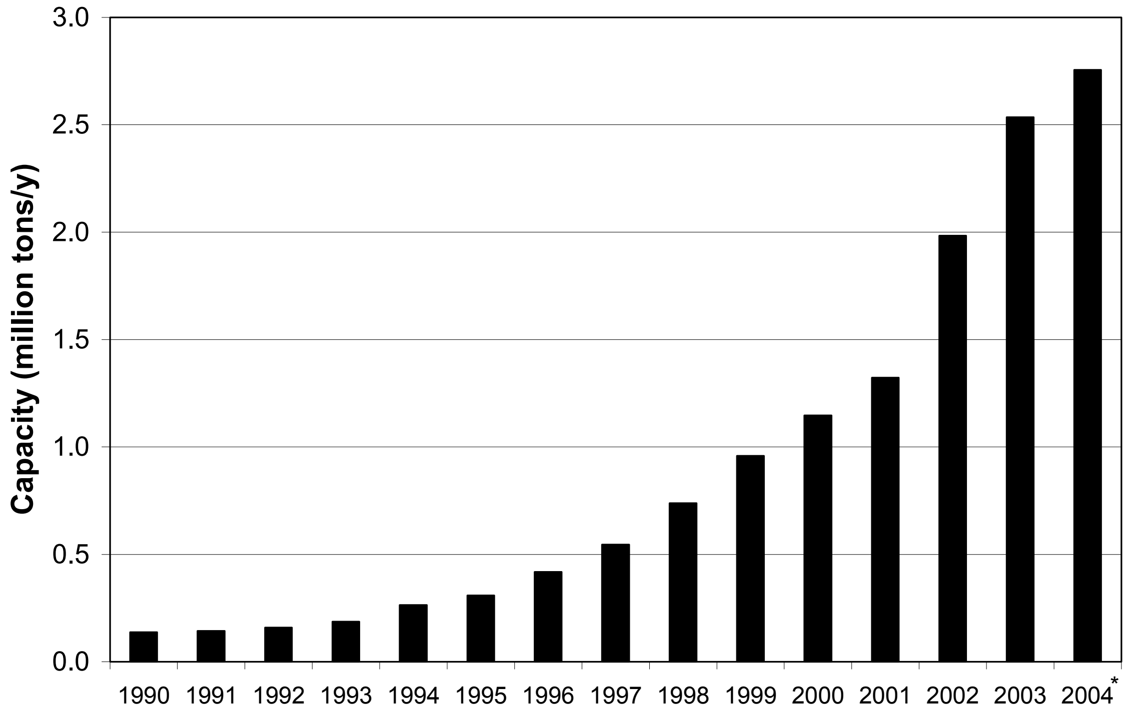

Fig. 3-13. Growth of Solid Waste Anaerobic Digester Capacity in Europe[123,124]
***Data were projected for 2004**

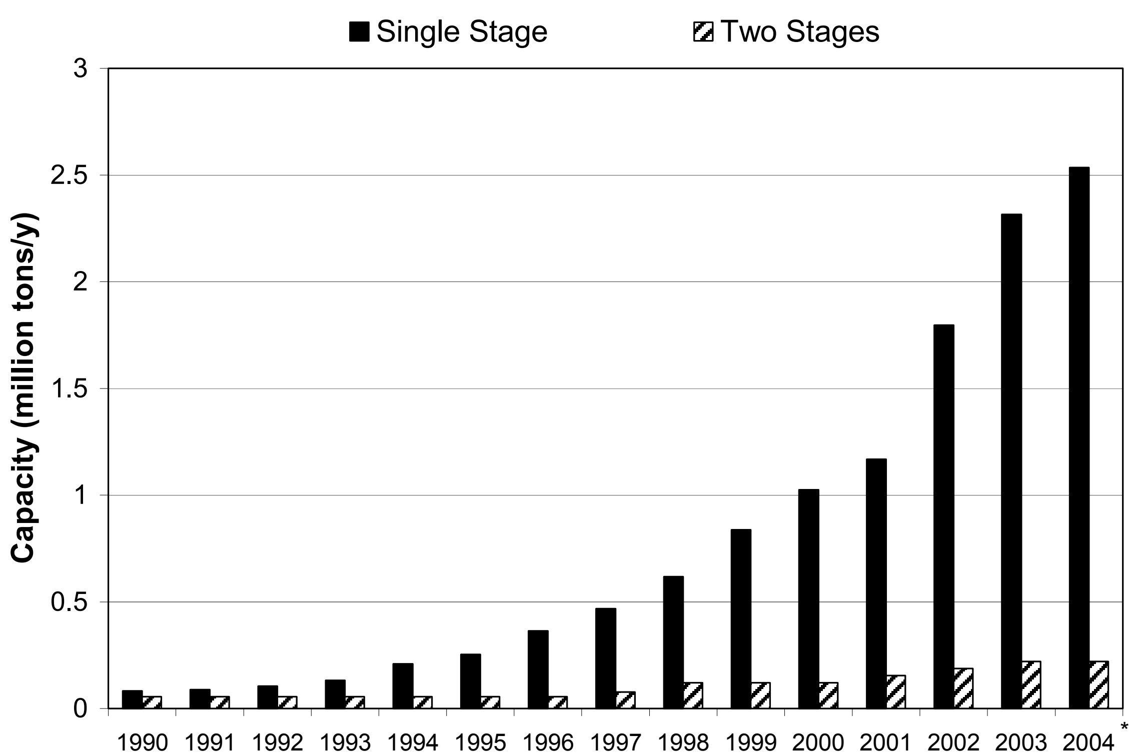

Fig. 3-14. Installed AD Capacity by Stage in Europe (adapted from De Baere (2000 & 2003))
***Data were projected for 2004**

Biogas Exploitation in California

Anthropogenic bio-methane in California captured for use or flared is primarily produced from three sources:

- In-place MSW at landfills producing landfill gas.
- Biosolids stabilization at waste water treatment plants.
- Animal manures from dairies or pig farms.

With respect to biochemical conversion of components of MSW in California, other than one full-scale landfill bioreactor demonstration project and conventional landfills, there are no existing biochemical processing facilities using anaerobic digestion or fermentation methods in the State. There are several proposed facilities including one for California State University – Channel Islands using a design developed at UC Davis. Recent announcements indicate that the City of Los Angeles and the City of Lancaster are investigating anaerobic digestion projects with Bioconverter LLC. In at least two jurisdictions in California that are investigating alternatives to landfill biochemical conversion is ranked among the finalists or even the only qualifying processes. One reason biochemical conversion processes are being favored by some local jurisdictions is because legislative policies allow diversion credit for biochemical processes but not for thermochemical conversion methods.

There are 311 active landfills accepting MSW in California. There are more than 2750 landfills that are closed, inactive, or abandoned in the state.[125] Currently, 51 landfills in the state are recovering landfill gas for use as energy (LFGTE) with a combined generating capacity of 210 MW, including 46.5 MW_e from the Puente Hills landfill operated by the Los Angeles County Sanitation District. Their distribution over several technologies is shown in Table 3-11. There are reportedly 26 other landfills planning to install LFGTE systems, which would provide an additional 28.8 MW_e.[126] Seventy landfills are recovering and flaring gas while the remaining, mostly smaller, landfills are venting their landfill gas. The landfills flaring and venting gas represent capacities of 65.76 and 31.41 MW_e, respectively.

Many wastewater treatment plants (WWTPs) produce sufficient methane to justify converting to heat and/or power, while others may flare the methane. Ten WWTPs in California have grid connected power generation and account for a combined gross electrical capacity of 39 MW.[127] The two largest are in Los Angeles County with a combined 24 MW_e from 770 million GPD wastewater (Table 3-12).

Table 3-11. Current California LFGTE activity by technology type.*

Technology	No. of Landfills	Total Electrical Capacity (MW)
Reciprocating Engine	32	112
Gas Turbine Combined Cycle	2	57
Steam Turbine	3	31
Gas Turbine	5	10
Direct Use (thermal)	7	-
Upgrade for Pipeline Use	2	-

* Adapted from Simons, G., et al. (2002). Landfill Gas-To-Energy Potential In California, California Energy Commission Staff Report 500-02-041V1.

Table 3-12 California WWTPs with power production from biogas

City	County	Plant Name	Waste Water Flow (million gal./day)	Capacity (MWe)
Oakland	Alameda	East Bay MUD Special District 1	78	2.2
Bakerfield	Kern	Bakersfield Plant 3	10	0.3
Los Angeles	Los Angeles	Hyperion TP	437	13.4
Whittier	Los Angeles	LACSD-JWPCP	331	10.9
Fountain Valley	Orange	Orange County Sanitation Dist. Plant 2	155	7.0
Riverside	Riverside	Riverside	30	0.5
Sacramento	Sacramento	Sacramento Regional WTP	181	2.8
San Francisco	San Francisco	San Francisco Oceanside WPCP	23	0.5
Watsonville	Santa Cruz	Watsonville WTF	12	0.3
Cunningham	Sonoma	Santa Rosa - Laguna WTP	15	0.6
Total Capacity (MWe)				**39**

Three operating dairy digesters produce electricity in California with a combined capacity of approximately 500 kW. One swine facility in the state has an operating digester. Additionally, 10 dairy manure digesters are planned or are under construction (Table 3-13). These projects are receiving incentive money through the Dairy Power Production Program (DPPP). This program was established from funds allocated by SB 5X (Sher, Statutes of 2001).

Essentially, the DPPP encourages biogasification with energy production to offset dairy power requirements and reduce air and ground water impacts associated with storage and treatment of livestock wastes. The California Energy Commission administers the program, which is managed by Western United Resource Development, Inc.[128]

Table 3-13 Livestock Manure Digesters, Existing and Planned

Location	County	Livestock Type	Number of Animals	Type of Digester	Status	Approximate Capacity (kWe)
Durham (Largerwerf Dairy)	Butte	Dairy	400		Operational	40
Chino (RP5 Digester)	San Bernardino	Dairy			Operational	370
Lidsay (Koetsier Dairy)	Tulare	Dairy			Operational	100
Mecca (Royal Farms)	Riverside	Swine	~1000		Operational	
Strathmore	Tulare	Dairy	1050	Cov'd Lagoon	Proposed/ Construction	120
Atwater	Merced	Dairy	4686	Cov'd Lagoon	Proposed/ Construction	300
Marshall	Marin	Dairy	237	Cov'd Lagoon	Proposed/ Construction	75
Lodi	San Joaquin	Dairy	1600	Cov'd Lagoon	Proposed/ Construction	160
Button Willow	Kern	Dairy	3600	Cov'd Lagoon	Proposed/ Construction	280
Visalia	Tulare	Dairy	1500	Plug Flow	Proposed/ Construction	260
Lakeside	San Diego	Dairy	600	Plug Flow	Proposed/ Construction	130
El Mirage	San Bernardino	Dairy	1900	Plug Flow	Proposed/ Construction	160
San Luis Obispo	San Luis Obispo	Dairy	175	Cov'd Lagoon	Proposed/ Construction	30
Tulare	Tulare	Dairy	1258	Cov'd Lagoon	Proposed/ Construction	150
Total Estimated Capacity (kW)						**2175**

Fermentation

Fermentation of biomass material into ethanol is fully commercial for sugar and starch based feedstocks such as sugar cane and corn. It is not yet commercial for cellulosic biomass because of high costs or low sugar yields and is the subject of intense research. Several facilities utilizing fermentation are being commissioned. The Masada OxyNol process will be under construction in Middletown, NY. This facility is permitted to process 230,000 TPY of MSW and 71,000 bone dry TPY of biosolids with an expected output of 8.5 million gallons of ethanol per year., There was no estimate of the waste CO_2 and process residuals given. A facility is also planned for the Genahol process in Grove City, OH. The facility will be designed for a 275,000 TPY capacity, which will yield 10 million gallons of ethanol, and no estimate of the waste CO_2 and process residuals given.

Table 3-14 lists company and/or process names with either existing or proposed biochemical processing of MSW facilities. Appendix H describes the individual processes in more detail.

Table 3-14 Companies using Biochemical Conversion Methods to Process MSW.

Company Name	Corp. Headquarters	Process Name	Process Type
Valorga	Montpellier, France	Valorga	Anaerobic digestion (OS – HS)
Wehrle Werk AG	Emmendingen, Germany	Biopercolat	Anaerobic digestion (MS-HS)
Wright Environmental Management	Ontario, Canada		In vessel composting
CiTec	Finland/Sweden	Waasa	Anaerobic digestion (OS – LS)
Linde-KCA-Dresden	Dresden, Germany		Anaerobic digestion & composting (MBT)
Kompogas	Glattbrugg, Switzerland	Kompogas	Anaerobic digestion (OS – HS)
U-plus Umweltservice	Ettlingen, Germany	ISKA	MBT followed by anaerobic digestion
Eco Tec	Finland	WABIO	Anaerobic digestion (OS – LS)
Organic Waste Systems	Gent, Belgium	Dranco	Anaerobic digestion (OS – HS)
BTA (Canada Composting in North America)	Munich, Germany (Ontario, Canada)	BTA	Anaerobic digestion (OS or MS – LS)
Arrow Ecology	Haifa, Israel	Arrow Bio	Anaerobic digestion (MS – HS/LS)
Onsite Power Systems	Camarillo, CA	APS (UC Davis)	Anaerobic digestion (MS- HS/LS)
Masada Resource Group	Birmingham, Alabama	CES Oxynol	Acid hydrolysis for ethanol production
Arkenol			Acid hydrolysis for ethanol production
WTE (w/ Genahol)l	Santa Maria, CA	Genahol/ BEI	Hydrothermal and acid hydrolysis for ethanol production

OS= One Stage MBT= Mechanical-Biological Treatment
MS = Multi Stage HS = High Solids LS= Low Solids

4 Products of Conversion

The products of each conversion technology are dependent on the chemical processes and to some extent, the feedstock used.

For thermochemical conversion, the products typically include:

Gasification:

- Fuel gases (CO, CH_4, H_2) or synthesis gas.
- Heat that can be transferred to the process to displace a fuel.
- Tars and other condensibles, if present after gasification process.
- Char and Ash.

Pyrolysis:

- Fuel gases (CO_2, CO, CH_4, H_2) containing less chemical energy than equivalent product gases for gasification of the same feedstock.
- Ash and char (fixed carbon not pyrolyzed) containing significant quantities of feedstock chemical energy.
- Pyrolytic tars and other high molecular mass hydrocarbons, also containing significant quantities of feedstock chemical energy.
- Pyrolytic oils and/or other condensables, containing significant quantities of feedstock chemical energy.

Biochemical processes can yield:

- Biogas (a mixture of methane and carbon dioxide). Biogas contains less chemical energy than the equivalent products from gasification of the same feedstock.
- Ethanol.
- Solvents, organic acids and other bio-based chemicals for refining to end products.
- Residues that can be used for compost/soil amendment/fertilizer if permitted by local regulations or a feedstock for thermochemical conversion.

The relative proportions of these different products depend on process type, operating conditions of the process, and feedstock characteristics. Nearly all of the products formed during a conversion process can be utilized in some market, although they must also be economically competitive. The fuel gases are most commonly combusted to produce energy for heat for reuse in the conversion process, and/or to produce electricity via appropriate prime mover. However, the synthesis gases produced by gasification of organic wastes can be use to produce a variety of fuels and chemicals. A sample listing of those chemicals is shown in Table 4-1.

Table 4-1. Fuels and Chemicals that can be Produced from Gas Feeds from Gasification of all Organic Components of MSW[129]

DIRECT SYNTHESIS	INDIRECT SYNTHESIS (VIA METHANOL)	OTHER SYNTHESES
Hydrogen	Formaldehyde	Olefins $\xrightarrow[Co/Rh]{H_2/CO}$ Aldehydes Alcohols
Methanol	Acetic Acid	
Ammonia	Methyl Acetate	
Carbon Monoxide	Acetic Anhydride	Isobutylene $\xrightarrow[H^+]{CH_3OH}$ MTBE
Medium BTU Gas	Vinyl Acetate	
Methane	Methyl Formate	
Higher (C_1-C[illegible]) Alcohols	Formic Acid	Acetylene $\xrightarrow[Ni]{CO}$ Acrylic Acid
Gasoline	Ethanol	
Diesel Fuel	Dimethyl Carbonate	
Isobutanol	Dimethyl Oxalate	Olefins $\xrightarrow[CO]{H^+}$ Highly-branched Acids
Isobutane	Gasoline	
	Diesel Fuel	
	Ethylene	RCOOH $\xrightarrow[RuO_2/HI]{H_2/CO}$ RCH_2COOH
	Propylene	
	BTX	
	Chloromethanes	Nitroaromatics $\xrightarrow[Pd]{CO}$ Isocyanates
	Methylamines	
	Methyl Glycolate	
	Ethylene Glycol	Terephthalic Acid $\xrightarrow{CH_3OH}$ Dimethyl Terephthalate

In pyrolysis processes, the remaining solid carbonaceous residue or char can also be combusted or gasified to produce electricity or sold as a by-product for the production of activated carbon. The ash can be separated into recyclable metal components, further processed into a vitrified slag, or disposed, depending on the quantities and toxicity of the materials involved.

The relationship between biochemical and thermochemical conversion technologies has been formalized in a recent publication from the office of the Biomass Program, EERE, DOE.[130] This DOE publication describes the efforts to develop bioproducts and biomass utilization in terms of two complementary technologies, production through biochemical fermentation of starch and sugars (the sugar platform) and by non-combustive thermochemical means (the synthetic gas platform).. The synergy among the DOE platforms is illustrated in the Figure 4-1.[131]

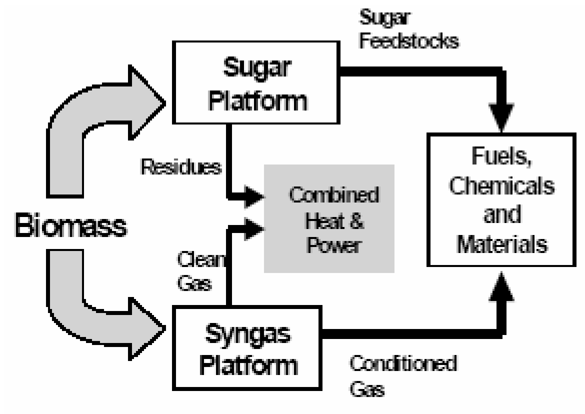

Fig. 4-1: Schematic of Materials Flows from Biomass to Fuels and Chemicals via either the Sugar or Syngas Platforms.

4.1 MSW as a Resource for Electric Power Generation

As discussed in earlier sections, the MSW that is currently disposed still contains large amounts of organic carbon (both renewable and fossil based carbon compounds). To illustrate the enormity of the resource, an estimate was made of the potential electricity generation if the entire California MSW disposal stream were to be converted using conventional means.* Table 4-2 displays the California waste stream characterization (which also appears in a modified form as Table 1-1) and the potential for electric power generation.

For estimating the amount of electric power generation capacity that could be developed from the waste stream that is currently disposed, it was assumed that the stream would need to be divided based on moisture content. This would not be necessary for those thermochemical conversion technologies such as steam pyrolysis that can process high moisture content organics. The high moisture components are assumed to be converted through biochemical systems (for example, anaerobic digestion). Though AD is suitable for high moisture feedstocks, the conversion is incomplete; with variable amounts of biogenic organic material left as a byproduct. Lignin and other recalcitrant biogenic organics are not converted by AD and remain as a residue for gasification, landfilling, or composting, although composting may not further degrade the residue. Food wastes are often highly degradable, however, and are added in some systems to increase gas production and generation rate. The aerobic processing of digester sludge through composting can further reduce volume, but anaerobic conditions maintained in most landfills may not reduce volume except over long periods of time. If only the produced biogas is converted to electricity (no energy production from the digestate), AD has an overall energy conversion efficiency (electrical energy out/feedstock energy in) of typically 10 to 20%, similar to some small thermochemical systems, although the latter can range substantially higher for larger advanced designs such as IGCC.

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* i.e., Combustion and steam-cycle power generation for dryer components and AD followed by reciprocating engine genset for high moisture components

Lower moisture components are assumed to be converted by thermal means such as gasification, pyrolysis, or combustion. The energy and/or heat in the product gases can be used directly in a fuel synthesis reactor, or in a boiler to produce electricity. Fuel gases from gasification or pyrolysis can also be used to run a gas engine or turbine for electricity production. These methods have overall energy efficiencies of electrical generation and fuel synthesis of 20-25%, although small generation systems designed for off-grid or local grid voltage support may have lower efficiencies. The estimates in Table 1-1 use 20% for thermal conversion to electricity efficiency. Biomass integrated gasifier combined cycles, BIGCC, have projected electrical conversion efficiencies of 35% or above, but are not yet fully commercial. Natural gas-fired combined cycles have electrical efficiencies above 55% by comparison, but utilize non-renewable fuel. The application of combined cycles to biogas produced by anaerobic digestion is a possibility but digesters tend to be small for the scales typically employed, and digestion of MSW or MSW organics is still developmental for the most part in North America. Biogas co-fired with natural gas in large combined cycle power plants is a way to improve net efficiency of biogas to electricity production if the opportunity exists. Fuel cells offer another high efficiency and clean option for biogas and fuel gases produced by thermochemical means, but these systems are also developmental and fuel purification is an issue.

In Table 4-2, the electrical generation estimates were calculated from the potential primary energy by applying the appropriate thermochemical or biochemical conversion efficiency and assuming an availability of 100% (meaning the conversion facilities operate 100% of the time).

The resulting potential electrical power generating capability from California MSW is substantial. For example, approximately 1670 MW_e of electric power could be generated if all the biogenic material (estimated at 25.5 million TPY) going to the landfill disposal stream were available for continuous power conversion, and another 690 MW_e of continuous electrical power could also be generated from the plastics and textiles components. Figure 1-1 displays some of the information from Table 4-2 graphically.

A total of 2370 MW_e of electrical power could be produced continuously throughout a one-year period by converting all the organic waste going to landfills in California. This is about 5% of total electric power generating capacity available to the state, assuming all the MSW power conversion was available contemporaneously. In contrast, the electrical energy generated from the power conversion of chemical energy in MSW is about 8% of annual state consumption.[†] Electrical energy that could be produced from the renewable (biogenic) portion of the MSW stream is equivalent to about 50% of the current amount of renewable electricity used in the State from all sources.[‡] Full conversion of all organic MSW to electricity is unlikely, and may

[†] Electricity consumption in California is ~ 275 TWh y^{-1}. Source: California Energy Commission.
[‡] http://energy.ca.gov/electricity/gross_system_power.html To the extent that plastics made from petroleum or tires are used in conversion to energy, that portion of the energy produced would not be considered renewable.

Table 4-2 California Disposed Waste Stream Characterization and Potential for Generation of Electrical Power.[132]

	Landfilled[a] (Mt)	Fraction of Total[a] (%)	Ash[b] (% wb)	Ash (Mt y^{-1})	HHV[b] (MJ/kg, ar)	HHV contribution to composite stream (MJ kg^{-1} as received)	Moisture[b] (%wb)	Landfilled (Mt dry)	HHV (MJ/kg, dry)	Primary Energy by Component (EJ)[c]	Primary Energy by Component (%)	Electricity Potential[d] (MWe)	(GWh y^{-1})
Paper/Cardboard	12.1	30.3	5.3	0.6	16	4.84	10	10.9	17.8	0.175	44	1111	9,730
Food	6.3	15.7	5.0	0.3	4.2	0.66	70	1.9	14.0	0.024	6	213	1,864
Leaves and Grass	3.2	7.9	4.0	0.1	6	0.47	60	1.3	15.0	0.017	4	78	680
Other Organics	2.8	6.9	10.0	0.3	8.5	0.59	4	2.6	8.9	0.021	5	135	1,180
C&D Lumber	2.0	4.9	5.0	0.1	17	0.83	12	1.7	19.3	0.030	8	191	1,676
Prunings, trimmings, branches and stumps	0.9	2.3	3.6	0.03	11.4	0.26	40	0.6	19.0	0.009	2	60	527
Biomass Components of MSW Total	**27.1**	**68.0**		**1.5**		**7.7**		**18.9**		**0.28**	**70**	**1787**	**15,657**
All non-Film Plastic	2.0	5.0	2.0	0.04	22	1.10	0.2	2.0	22.0	0.040	10	253	2,212
Film Plastic	1.6	3.9	3.0	0.05	45	1.76	0.2	1.6	45.1	0.064	16	403	3,530
Textiles	0.8	2.1	7.0	0.06	17.4	0.37	10	0.8	19.3	0.013	3	84	735
Non-Renewable Carbon Compounds Total	**4.4**	**11.0**		**0.15**		**3.23**		**4.3**		**0.12**	**30**	**739**	**6,477**
Other C&D	2.7	6.7	100	2.7	0	0		2.7					
Metal	2.4	6.1	100	2.4	0	0		2.4					
Other Mixed and Mineralized	2.1	5.3	100	2.1	0	0		2.1					
Glass	1.1	2.9	100	1.1	0	0		1.1					
Mineral Total	**8.3**	**20.9**		**8.3**		**0.0**		**8.3**		**0**	**0**	**0**	**0**
Totals	**39.8**	**100**		**10.0**		**10.89**		**31.6**		**0.394**	**100**	**2527**	**22,134**

a)California waste stream composite data is from the 1999 Waste Characterization study (http://www.ciwmb.ca.gov/WasteChar/Study1999/OverTabl.htm), Accessed 1 Sept., 2003 Disposal amount for 2003 is taken from; http://www.ciwmb.ca.gov/lgcentral/Rates/Diversion/RateTable.htm. 1999 composition data was used for calculating 2003 energy potential

b) Adapted from Tchobanalglous, G., Theisen, H. and Vigil, S.(1993),"Integrated Solid Waste Management", Chapter 4, McGraw-Hill, New York & Themelis, N. J., Kim, Y. H., and Brady, M. H. (2002). "Energy recovery from New York City municipal solid wastes." Waste Management & Research, 20(3), 223-233.

c) EJ = 10^18 J (exajoule) and is approximately equal to 1 Quad (1 Q = 1.055 EJ)

d) Electricity calculations assume thermal conversion means for low moisture stream (paper/cardboard, other organics, C&D Lumber, all plastics and textiles) and biochemical means (anaerobic digestion) for high moisture components (food and green waste). Energy efficiency of conversion of matter to electricity by thermal means is assumed to be 20%. Biomethane potentials of 0.29 and 0.14 g CH_4/g VS for food and leaves/grass mixture respectively are assumed for biogas production that is converted at 30% thermal efficiency in reciprocating engines. Capacity factor of 1 is used.

never compete commercially with coal, and nuclear power plants, but solid waste nonetheless represents a significant potential source of energy or raw materials for the state.*

For the processes examined in this report, the energy output for the thermochemical processes typically varied for approximately 250 to 700 kWh per ton of material, with an average energy output of approximately 450 kWh per ton. A plot of potential electrical energy output per ton of input material is provided in Figure 4-2 based on analysis by Juniper Consulting Services Ltd., as well as some information provided by vendors.[133] Overall, the amount of energy that is derived for different processes is a function of both the feedstock and the method used to produce the energy. Feedstocks with high calorific values, such as plastics, tires or rubber, can produce generally higher energy outputs. On a per mass basis, the greater the preprocessing, particularly with respect to removal of inorganics, the greater the potential energy output. The efficiency of the reaction process itself and auxiliary processes also affects the net amount of energy that can be produced, i.e. the kWh (net) per ton MSW in Figure 4-2.

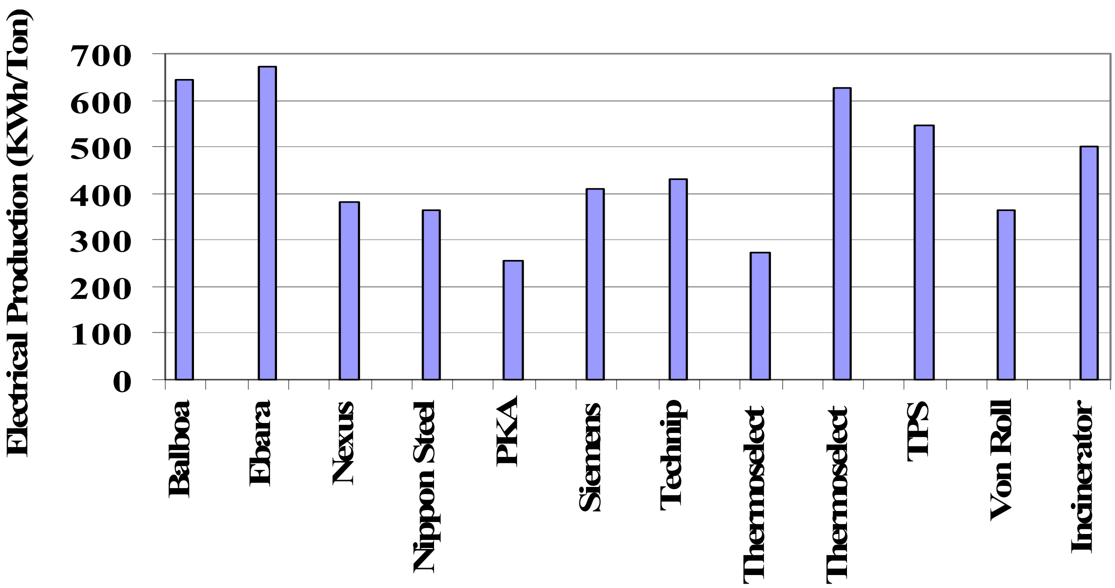


Figure 4-2. Net Energy Export for Various Thermochemical Processes vs. Conventional Incineration

In examining the environmental consequences of conversion technologies, it is important to compare emissions values with other technologies. Many California power plants use natural gas combustion to produce electricity. Waste-to-energy facilities based on mass burn incineration techniques are also used at three locations throughout the state (Long Beach, Commerce, and Stanislaus County near Modesto), so it is important to also make comparisons with these facilities.

* This analysis applies only to the current waste stream going to landfill. CIWMB estimates that approximately 8 million tons of MSW material go to compost, ADC, or solid fuel combustion facilities annually and only ~31% (4.8 million tons/y) of waste paper is diverted (1997), http://www.ciwmb.ca.gov/Paper/ Accessed October, 2003) The amount of urban wood waste or C&D lumber estimated to be currently consumed in power production facilities is 1.5 million TPY.

4.2 Products of Thermochemical Processes

In this section, the range of potential products that can be obtained through the use of the fuel or synthesis gases, producer gases, oils, and solid residuals from the conversion technology process is examined. The products are examined with respect to marketability, environmental attributes, and any potential barriers to market penetration.

4.2.1 The Effects of Feedstocks and Process Variables on Product Types

Before examining the product types and product marketability in detail, it is important to understand how the product streams resulting from different conversion technologies can be changed through differences in feedstocks and process variables. The organic components of the conversion products can include gases, liquids, and solid materials such as char with the relative proportions of each depending on the method of decomposition and the parameters, such as temperature and pressure. The influences of these process variables have been discussed in greater detail in Chapter 3. Briefly, processes conducted at lower temperatures, such as pyrolysis, tend to produce more liquid products, while higher temperature processes such as gasification tend to produce more gaseous products. Pyrolysis processes combined with rapid quenching of the produced vapors can also be preferentially used to create a liquid pyrolytic product.

The chemical composition of the feedstock also plays an important role in the chemical mix of the products. The chemical composition of carbonaceous feedstocks can generally be reported using two methods, ultimate and proximate analyses. Ultimate analysis reports the percentage composition of the major chemical elements present in the material, usually carbon C, hydrogen H, oxygen O and nitrogen N, with sulfur S, and chlorine Cl as minor elements. The proximate analysis reports the moisture content, volatile matter, fixed carbon and ash as mass fractions of the as-received (ar) material. The ultimate analysis is usually stated on a dry basis, with the inorganics (other than N and S, and sometimes Cl) simply lumped together as "ash." From this ultimate analysis, a dry-ash-free (daf) analysis result can be calculated, and investigations that compare fuels for heat content and combustion/emission purposes often use the daf basis. However, if an investigation addresses issues of slagging, fouling, corrosion and deposition, the ash content must be broken down into the "ash elements" which are the Si, Al, Fe, Na, K, Ca, etc in the ash fraction.

For MSW, typical values for the ultimate and proximate analyses of MSW components are given in Tables 4-3 and 4-4. Table 4-3 shows the proximate analysis for municipal waste in Kuala Lumpur, Malaysia,[134] although the composition of MSW from Malaysia may be slightly different from the MSW from California or other parts of the US. If the pyrolytic process is allowed to go to completion, all the volatile matter will eventually leave the solid material and become either gas or vapor phase compounds that contain all the elements in the feedstock except the fixed carbon and the silicon oxide in the ash. From these data, the residual pyrolytic solid material (char) contains over 30% of the original MSW on a dry basis. This char would contain about 32% carbon and 68% ash material (assumed to be made from pure silicon dioxide).

Table 4-3. Proximate Analysis of Municipal Solid Waste in Kuala Lumpur, Malaysia

Moisture	wt% (dry)
Volatile matter	69.70%
Fixed carbon	9.71%
Ash	20.58%

Table 4-4 shows the ultimate (or elemental) analysis of MSW from several locations, including Kuala Lumpur. From the data, one can create a molecular distribution from the elemental analysis.

Table 4-4. Ultimate Analysis of MSW from Several Locations

	(% by weight, dry basis)					
	C	H	O	N	S	Ash
California statewide average (full Stream)[a]	36.2	4.9	27.0	0.5	0.1	31.3
New York City (full stream)[b]	39.3	5.1	30.1	0.6	0.1	24.8
Kuala Lumpur (full stream)[c]	46.1	6.9	28.1	1.3	0.2	17.1
California statewide average (Combustible portion)[a]	49.1	6.7	36.6	0.7	0.2	6.7

a).Based on CA characterization (Table 1-1)

b).Themelis, N. J., Kim, Y. H., and Brady, M. H. (2002). "Energy recovery from New York City municipal solid wastes." *Waste Management & Research*, 20(3), 223-233.

c).Kathiravale, S., Muhd Yunus, M. N., Sopian, K., Samsuddin, A. H., and Rahman, R. A. (2003). "Modeling the heating value of Municipal Solid Waste**1." *Fuel*, 82(9), 1119-1125.

For the ultimate analyses above, the average chemical formulas (ash free basis) are

CA (full stream ave.) $C_6 H_{9.72} O_{3.36} N_{0.07} S_{0.01}$

NY City $C_6 H_{9.29} O_{3.45} N_{0.08} S_{0.01}$

Kuala Lumpur $C_6 H_{10.64} O_{2.75} N_{0.14} S_{0.01}$

Product streams are limited by both fundamental thermodynamic principles and the parameters described in the proximate analysis. From a thermodynamic analysis, it can be shown that the chemical energy in the pyrolytic products must always be less than the chemical energy in the feedstock. The solid char, for example, will typically have the chemical energy associated with the fixed carbon constant in the feedstock, since the ash contains no recoverable energy. However, the pyrolytic gases and vapor can contain as much as the feedstock chemical energy minus that contained in the char. These pyrolytic products can be burned separately to produce electric power and heat, if that is the purpose of the pyrolysis processes.

4.2.2 Products Derived from Gaseous Byproducts of Thermochemical Processes

For the gas products of pyrolysis or gasification of MSW, the most typical use is in the production of electricity or process heat. Although use of gaseous products for electrical power production is typical in other parts of the world, it is likely that such technologies would face stiff resistance from environmental groups even if adhering to the strictest environmental constraints. This is discussed further in Chapter 5. As a result of these potential barriers, it is important to examine other potential products that can be produced from gaseous residuals.

Before 1990 nearly all of the products from synthesis gas were used for the production of chemicals and fuels such as Fischer-Tropsch diesel.[135] The percentage of gasification facilities producing electrical power, and correspondingly utilizing post-combustion of synthesis gas increased during the 1990s and has risen significantly since 2000 due to demand and deregulation of electricity markets around the world. On a worldwide basis, however, the capacity of gasification for chemicals, fuels, and gases is still larger than that for power production.

The composition of the synthesis or fuel gas can play an important role in the types of chemicals that can be produced. As discussed previously, pyrolysis and gasification reactors form product gases such as CO, H_2, CH_4, CO_2, N_2, and light hydrocarbons. These products are considered synthesis gases if they contain higher percentages of CO and H_2 and fuel gases if they principally consist of CH_4 with lighter hydrocarbons. Sample compositions of gaseous products are provided in Table 4-5 for different pyrolysis and gasification processes. These results show that the range of gas products can vary considerably depending on the specific process being used.

Table 4-5. Gaseous Products for Various MSW Pyrolysis / Gasification Facilities / Technologies (in % of total gas composition)[136,137,138]

	CH_4	H_2	CO	CO_2	N_2	O_2	Ethane	Ethene	H_2O
Brightstar	30	35	25	9	<1%				
Enerkem (air)	3.0	6.0	13.6	15.5	58.0		1.0	1.7	
Enerkem (O_2)	4.0	12.0	15.0	26.7	26.3		2.0	1.8	
Foster Wheeler		5.9	4.6	12.9	40.2				33.0
GEM	22.6	30.5	19.3	17.9	1.3	10.2	1.9	3.4	
Krupp-Uhde		23.5	59.8	1.8	14.9				
PKA	2.5	17	11	12	56	1			
Pyromex	11	33	36	18				2	
Thermoselect		34.7	36.5	25					
Thide-Eddith	16	12.7	19.1	28.8			4.9	5.5	

The introduction of a reactant into gasification processes can provide some additional flexibility in changing the composition of the gaseous products, albeit with higher initial capital costs. Rensfelt and Östman (1996)[139] examined the tradeoffs between pyrolysis and gasification processes as part of a comprehensive IEA report. They concluded from their estimated investment costs and energy efficiencies that combinations of gasification and syngas combustion plants may be feasible, in comparison with combustion facilities for heat production. For power generation, the gasification processes with product syngas cleaning held a potential advantage over combustion facilities due to lack of high temperature corrosion on steam superheaters. They also concluded that pyrolysis processes producing liquid products, in combination with combustion of those products, do not provide any advantage over gasification since the cleaning of the liquid pyrolytic products is far more complicated than cleaning of the syngas, and the overall energy efficiency of pyrolytic processes is markedly lower than for gasification. Finally, they found that pyrolytic methods yielding both char and liquids from contaminated waste fuels have very low or negative product value.

Due to the heterogeneous nature of MSW, the production of chemicals, fuels, and synthetic gases from a MSW gasification facility would likely require additional control, when compared with similar processes using coal or petroleum sources. The temperature, pressure, gasifying agent, and the reaction rate, would be of great concern in this process. One method that ensures a more homogenous feedstock is to have the feedstock introduced into the gasifier as a liquid slurry. By metering the flow of the slurry and the pressure under which it is delivered into the gasifier, the stoichiometry can be controlled and even linked to the carbon content of the feedstock. However, care must be taken with this method of delivery, as pollutants and contaminants may require additional control. Both the Texaco gasifiers and the UCR hydrogasification system use this method of feedstock control.

Chemicals for Industrial and Agricultural Uses

Ethylene

Ethylene is an important petrochemical feedstocks used primarily for the production of vinyl chloride monomer (VCM), and polyvinyl chloride (PVC) plastics. Nearly 93 million tons of ethylene are produced annually in chemical plants worldwide, using an energy intensive process that consumes 2.5 quadrillion Btu per year. A conventional ethylene production plant pyrolyzes naphtha, a residue from petroleum refining. The economies of scale usually require these plants to be adjacent to oil refineries.

Various methods have been employed to produce ethylene from coal stocks, as a substitute for crude oil. The most successful commercial operation has been undertaken by SASOL in South Africa. In this process, synthesis gas produced by the gasification of coal using any of the commercially proven gasifiers is converted into the full range of synthetic petroleum products including ethylene using reactors based on the Fischer-Tropsch (F-T) paraffin synthesis process.

If ethylene is not used on-site, it is transported by pipeline or by tanker to other plants. Approximately half of the annual worldwide production is used for the manufacturing of polyethylene. The rest of the ethylene is used to make propylene, butadiene and benzene, which are eventually used to make fiber, plastic and resin products, as shown in Figure 4-3.

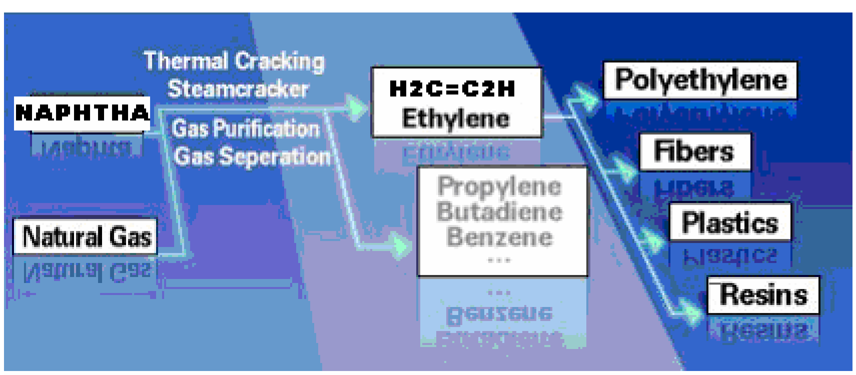


Figure 4 - 3: Flow Chart of Possible Products from Synthesis Gas.

Ammonia Based Chemical Fertilizers

The hydrogasification or hydro-cracking of organic compounds containing atomic nitrogen almost always produces ammonia gas, which can be removed from the gas product stream by condensation processes similar to those used to remove water. Once this is removed as an aqueous base, usually as ammonium hydroxide, numerous methods are available to produce a range of ammonia compounds used in chemical fertilizers. Ammonium nitrate and urea are by far the most common agricultural chemicals used (Table 4-6). The removal of sulfur during gas cleaning operation could also be used to synthesize ammonium sulfate, another useful fertilizer.

Table 4-6. Form and Analysis of Commonly Used Agricultural Chemicals.

Name	Grade	Chemical	Form
Anhydrous ammonia	82-0-0	NH_3	Gas
Urea	46-0-0	$(NH_2)_2CO$	Solid prills
Ammonium nitrate	34.5-0-0	NH_4NO_3	Crystalline
Ammonium sulfate	21-0-0-24	$(NH_4)_2SO_4$	Crystalline
Monammonium phosphate	11-55-0 12-52-0	$NH_4H_2PO_4$	Solid prills
Ammonium phosphate sulfate	16-20-0-14	$NH_4H_2PO_4$ + $(NH_4)_2SO_4$	Solid prills
Potassium chloride	0-0-69-0	KCl	Crystalline

Liquid Fuels

Fischer-Tropsch Synthetic Fuels

Fischer-Tropsch (F-T) is a process for producing mainly straight-chain hydrocarbons from a synthesis gas rich in CO and H_2. Catalysts are usually employed. Typical operating conditions for FT synthesis are temperatures of 390-660° F and very high pressure depending on the desired products. The product range includes light hydrocarbons such as methane (CH_4) and ethane (C_2H_6), liquefied petroleum gas [LPG] (C_3-C_4), gasoline (C_5-C_{12}), diesel (C_{13}-C_{22}), and waxes ($>C_{23}$). The distribution of the products depends on the catalyst and the process conditions (temperature, pressure, and residence time). The synthesis gas must have very low tar and particulate matter content. Biomass derived synthesis gas for FT liquid production is feasible and is not limited due to gas cleaning issues.[140] Greater details of the history, chemistry, and commercialization of Fischer-Tropsch diesel fuel is provided in Appendix I.

A number of studies have shown that F-T diesel can provide reductions in emissions relative to more conventional diesel fuels. Thus, the displacement of petroleum diesel fuel should provide a net reduction in emissions. Several preliminary engine studies demonstrated the emissions reductions of between 30-60% for total hydrocarbons, 20-30% for carbon monoxide, 10-20% for nitrogen oxides, and 20% for a pure F-T compared to a conventional national diesel No. 2.[141,142] Other researchers have also made comparisons in emissions between F-T diesel and California reformulated diesel, which has more stringent requirements than national diesel No. 2. Tests in a 1994 Navistar engine showed about a 30% reduction in total hydrocarbon emissions, along with 5-10% reductions in CO, NO_x and PM for a 100% F-T diesel versus a California reformulated diesel fuel.[143] Additional tests also showed reductions of 12% in NO_x and 24% in PM for a 100 percent F-T diesel compared with a California diesel using chassis dynamometer tests on heavy-duty diesel trucks.[144] Studies have also shown that more highly refined, straight petroleum diesel with a higher paraffinic content, higher cetane number and lower aromatic content, (similar to F-T diesel) tends to reduce emissions from diesel engines over a broad range of vehicle types.[145,146]

Methanol as a Liquid Fuel

The Liquid Phase Methanol (LPMEOH™) process integrates gasification with chemicals production. It was demonstrated on a commercial scale by a partnership between Air Products and Chemicals, Inc., and Eastman Chemical Company. Application of this technology can enhance the economics and efficiency of power generation by producing a clean-burning, storable liquid (methanol) from syngas during periods of low power demand. The methanol can be used to fuel combustion turbines during peak demand. The main uses for methanol are in the production of chemicals, such as formaldehyde, acetic acid, and other derivatives, and as a fuel. It can be also dehydrated to produce olefins, a large and growing market. Demonstration of the LPMEOH™ process has increased the experience base and reduced the commercial risk for future operations, whether integrated with chemicals production or with IGCC power production. Together these technologies can fill local needs for electric power, transportation fuels, and chemicals.

Synthetic Ethanol Production

In addition to methanol, other alcohols such as ethanol can be produced from syngas. Experience in commercial manufacturer has been extensive worldwide; for example Union Carbide has had facilities operational since the 1930s. Use of synthetic ethanol is second only to water as a cleaning solvent. It is also one of the key raw materials used in the manufacture of plastics, lacquers, polishes, plasticers, perfumes and cosmetics.

Ethanol is also being more widely used in commercial gasoline as an oxygenate to reduce exhaust emissions that contribute to smog formation, and in California as a replacement to MTBE. The benefits of oxygenate and ethanol use in gasoline have been studied extensive in a number of studies by automotive and oil company collaborations and government agencies,[147,148,149] with ethanol providing total hydrocarbon and carbon monoxide reductions and unclear effects for NO_x. The potential benefits of oxygenates in gasoline will likely decline, however, as more advanced vehicle technologies become more widespread. Ethanol is also know to increase the Reid Vapor Pressure (RVP) of gasoline,[150] thus steps must be taken to ensure that evaporative emissions and fleet-wide RVP under in-use conditions will not increase. Ethanol can also provide emissions benefits when added to diesel fuel, although proper precautions must be taken with ethanol diesel blends since they have a much lower flashpoint than diesel fuel and a higher vapor formation potential in confined spaces.[151]

Dimethyl Ether (DME)

Dimethyl ether (DME) is an environmentally-friendly compound that is used as a propellant in about 10 billion aerosol spray cans each year. DME could also become a significant source of energy in the decades to come. DME is a clean and safe fuel that can be made from natural gas, coal or biomass. In addition to its applications in power generation, domestic fuel use and diesel engines, DME has a potential use in fuel cells. It is environmentally benign and can be handled like LPG. The International Energy Agency (IEA) believes that DME offers a great potential as a multi-source, multi-application fuel and expects DME to achieve recognition as an alternative to conventional fuels. DME would also be an ideal candidate for the diesel-electric hybrids, as it has already been shown to be a clean alternative diesel fuel and has fewer complications in transportation and storage than hydrogen.

DME is a useful building block in producing important chemicals such as dimethyl sulfate and high-value oxygenated compounds. It is also used as an aerosol propellant in products including hair spray, perfumes and shaving cream due to its environmentally friendly properties. Furthermore, DME has been attracting more attention as an alternative clean fuel for diesel engines. It has excellent properties for compression ignition combustion, a cetane number of over 55 and zero sulfur content. Engine tests carried out by Amoco, Haldor Topsoe, etc. have indicated that with minor fuel system modification, engine operation with a thermal efficiency equivalent to that of traditional diesel fuel, accompanied by much lower NO_x emissions, smokeless combustion and less engine noise can be achieved.

Hydrogen as a Fuel Gas

Another option for co-production is the manufacture of hydrogen from syngas. Hydrogen is a critical ingredient in refinery processes, such as hydrocracking and hydrotreating, and is also a starting material for ammonia production. Hydrogen production is being considered as an integral part of DOE's Future Fuels Program, which targets the development of clean fuels that will require major modifications to, or replacement of, the existing transportation fuels infrastructure.

It is hoped that future generation fuels will be obtainable from domestic natural gas, petroleum, refinery and organic (municipal liquid and solid) wastes, coal and other suitable carbonaceous feeds. Fuels made from the conversion of organic wastes, especially MSW, could be cost competitive in this context. As part of an advanced transportation system, the widespread deployment of these future fuels would enable vehicles to achieve zero to near-zero emissions of criteria pollutants and greenhouse gases. They will, however, likely require some adjustment to today's consumer patterns and fueling/refueling requirements. Examples of advanced vehicle systems that will require these future fuels include diesel-electric hybrids and fuel cell powered vehicles. These alternative fuels, especially when derived from organic wastes, will offer the prospect of high-efficiency transportation systems having minimum environmental impact.

4.2.3 Pyrolytic Oils

Pyrolytic liquids are complex mixtures of hydrocarbons that can be combusted for energy production or utilized in the production of chemicals. The liquid fraction can contain a range of species including acids, alcohols, aldehydes, ketones, esters, heterocyclic derivatives and phenols along with varying contents of water. Some properties of pyrolysis oils for different conversion technologies are provided in Table 4-7.

For many processes, residual pyrolysis oils are typically utilized for their chemical energy either on site or at an energy generation facility. From an energy standpoint, pyrolysis liquids typically have heating values of only 40-60% of that for the hydrocarbon fuels.[152] Combustion tests and practical experience have shown that these oils can be burned effectively in standard or slightly modified boilers and in engines similar to those used with standard hydrocarbon fuels. However, there are some issues with corrosion and thermosetting that have proven difficult. On the other hand, testing has showed some promise with the oils that have been refined.

Table 4-7. Pyrolysis Oil Composition for Different Processes/Feedstocks

	Alcyon	Conrad	Dynamotive	Ensyn
Feedstock	Tires	Plastics	Wood	Wood/bark
Specific Gravity	0.937	0.86	1.2	1.2
Heating value (Btu/lb.)	18,480	18,500	7,134	6,876
pH			2.3	
Carbon (wt. %)	87.4	87.88		54.5
Hydrogen (wt. %)	6.2	11.98		6.4
Ash (wt. %)	0.01	0.04	<0.02	0.16
Water content (wt. %)			23.3	24
Total aromatics (wt. %)		39.0		
Total aliphatics (wt. %)		40		
Olefins (wt. %)		12.6		

For most applications, raw pyrolysis oils will require upgrading or refining before use. Pyrolysis oils tend to have a high water content that can have a negative impact of ignition and combustion effectiveness. Some of the heavier hydrocarbon components can have an impact on the fueling system or potentially clog injectors. In the case of organic acids, there is also some potential for corrosion of system parts. The high viscosity of the pyrolytic oils has also discouraged their use, as well as their tendency to solidify close to room temperature. However, recent studies by ChevronTexaco at their Montebello facility have demonstrated that pyrolytic oils could be used as liquefying agents to facilitate the melting of waste plastics and polymer feedstocks to form pumpable slurries for controlled feed into high-pressure gasifiers. In this case, both the pyrolytic oils and the molten plastic-polymer mix can be gasified to convert a high fraction (typically over 85%) of the carbon in this feedstock into gases.

From a chemical engineering standpoint, a range of possible chemical compounds can often be found in pyrolysis oils that have industrial uses. These include, but are not limited to, phenol species, acetaldehyde, formaldehyde, pentanes/pentenes, BTX (benzene, toluene, and xylene) chemicals, and activated carbon.

The making of substitutes for petroleum distillates is one potential use of pyrolysis oils. ACM Polyflow has developed a process that converts polymer plastics into an oil that yields 94% distillates, of which 70% are aromatic hydrocarbons.[153] Conrad Industries has also produced a pyrolysis oil from post-consumer plastics and tires that can be used as a sweet crude oil pre-cursor feedstock for petrochemical manufacturer or in mini-refineries as a coker feedstock.[154] BP has also examined opportunities in utilizing thermal cracking processes for the chemical recycling of plastic wastes into a generic hydrocarbon feedstock.[155]

Ensyn has a range of fast pyrolysis facilities that produce bio-oils from wood-base waste that have been used in several different types of applications.[156] Initially, the bio-oils were used for the manufacture of food flavorings with applications also for fragrances and pharmaceuticals. More recently, Ensyn has developed some commercial natural polymer and resin products that can be substituted for petroleum-based compounds in adhesives and other products. One application of these resins is in the manufacture of engineered wood products such as oriented strand board and plywood. Dynamotive is another pyrolysis technology for converting wood-based feedstocks to a bio-oil that can be used as a substitute petroleum-based products. Dynamotive is examining the use of their bio-oil for a number of different products including substitute diesel fuel, air pollution products such as biolime or noxolene, slow release fertilizers, and specialty chemicals such as acetic acid, formic acid, and hydroxyacetaldehyde.[157]

4.2.4 Solid Residue Products

The solid residues from thermal conversion products include a carbonaceous char and an inorganic ash. The char is typically used in a combustion process for energy generation or sold as a byproduct. The energy from the char combustion is typically used for electricity generation or process heat, much like the energy produced from the gaseous and liquid products. The char can also be marketed off-site for combustion applications. The carbonaceous char can also be sold as a byproduct that has uses in a number of applications including activated carbon, road and roofing products, pigments, rubber goods, and applications in oil remediation and agriculture. The upgrading of the char to activated carbon can typically be done by steam pyrolysis or gasification that provides a greater porosity to the produced char.

Several processes or methods of disposal are used for the inorganic ash component. For some processes, no further processing of the ash is performed and residual is simply disposed of via landfill. For direct disposal of the ash, leachability is an important issue as discussed further in Chapter 5. Other processes utilize more extensive post-processing to make greater use of the ash residual. For processes utilizing a fluidized bed reactor, the ash can, in some cases, be recycled for use as bed material. For those processes that recycle the ash, one of the first steps is typically the removal of the metals via a magnet for recycling. In some cases a water wash is also performed. The ash can be further processed using a vitrification process. The vitrification process involves the exposing of the ash to an oxygen rich gas mixture at elevated temperatures of approximately 1300-1400 °C. The resulting product is a glassy material that can be used for building blocks, or in the ceramics industry, tile industry or construction industry. Other processes can incorporate a smelting furnace that can be used to produce a Cu-Fe alloy and a residual slag that can be used in the cement industry.

4.3 Biochemical Product Types

High moisture feedstocks are perhaps most appropriately converted through biochemical systems (anaerobic digestion, for example). Though AD is suitable for high moisture feedstocks, a major disadvantage of AD is that conversion is incomplete. Although only about 1/3 of the organic material in MSW may be lignin that cannot be converted, the hemicellulose and cellulose components are only partially converted in any biochemical system that has practical economic feasibility. This results in over 50% of the input material not being converted. Thus, the lignin and other recalcitrant biogenic organics that are not converted into fermentable feedstocks remain as residue for thermal conversion, composting, or landfill.

Biomass can be hydrolyzed to create fermentable sugars for producing ethanol. The lignin component is also unconvertible in a hydrolysis and fermentation system. Sugars can also be converted to levulinic acid and citric acid. Levulinic acid is a versatile chemical that is a precursor to other specialty chemicals, fuels and fuels additives, herbicides, and pesticides. The largest application for citric acid is in the beverage industry, which accounts for about 45% of the market for this product. Citric acid is also used in a wide variety of candies, frozen foods, and processed cheeses and as a preservative in canned goods, meats, jellies, and preserves (See Figure 4-4 for a diagram showing potential biobased chemicals). Residual acids in the sugar stream can be neutralized using lime. The use of lime as a neutralizing agent yields gypsum, which can be sold as a soil amendment or to wallboard manufacturers.

Carbon dioxide is a potential byproduct from some biochemical processes as it is produced along with the primary product. For instance, biogas from AD systems consists of 40-60% (by volume)

CO_2 for which separation and recovery is possible. This is possible when the biogas quality is upgraded to pipeline or vehicle fuel standards. This process separates separates the CO_2 from the methane and could be used in applications requiring carbon dioxide. Fermentation to ethanol produces CO_2 as well. Whether or not CO_2 recovery from biochemical processing would be commercial at the scale of waste processing likely to be developed was not investigated.

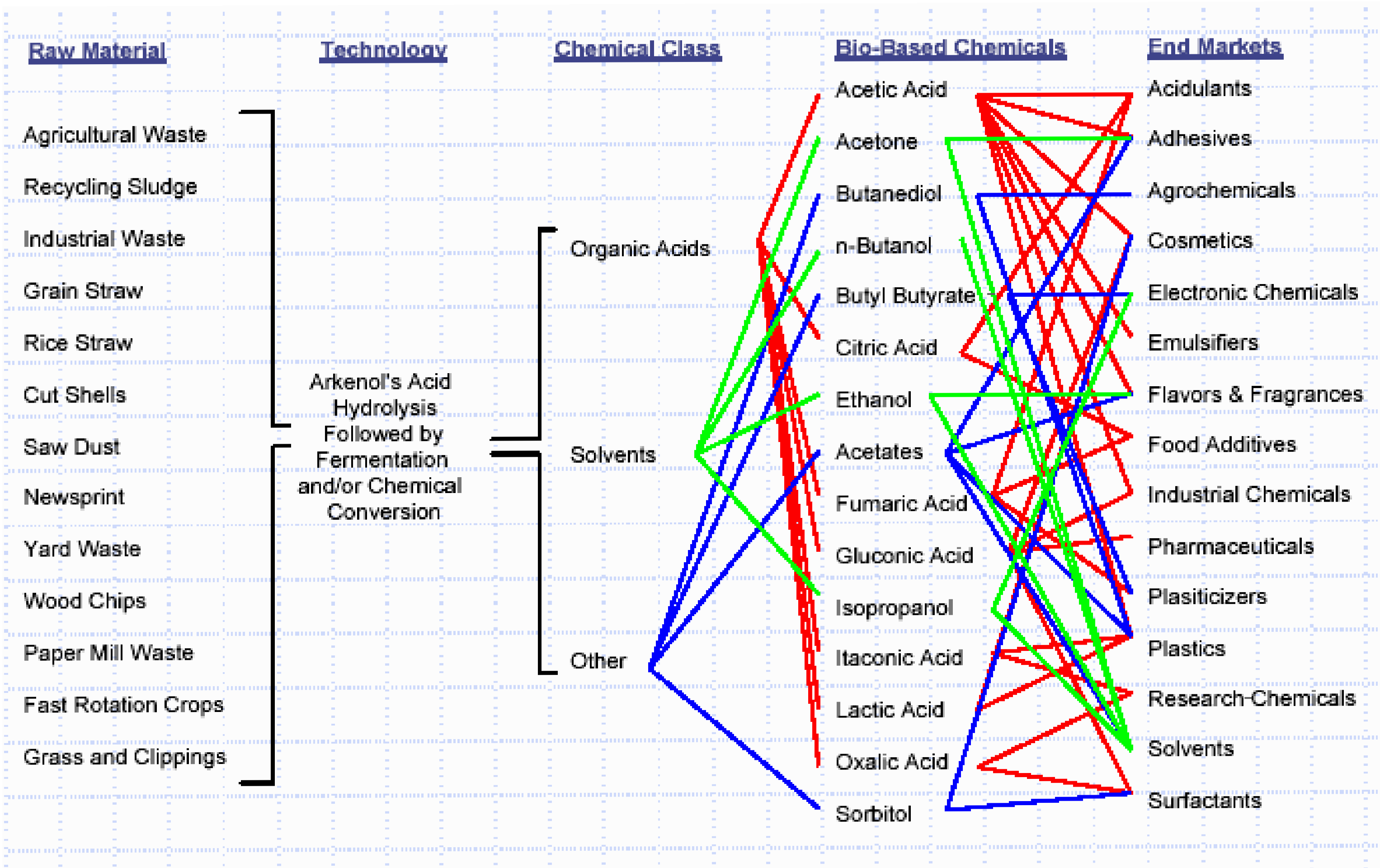


Figure 4-4 Biomass Feedstocks and Potential Biobased Chemicals (courtesy Arkenol)

5 Environmental Impacts

Some environmental performance aspects of existing waste management practices are well known while others are not (for example, the long-term consequences of dry-tomb landfill technology are uncertain). Established modern solid waste combustion with energy recovery facilities have well documented environmental performance, as do many of the incinerator ash melting technologies in use in Japan. The growing biochemical conversion industry in Europe also has well characterized environmental performance, as does existing aerobic composting technology. While there is disagreement regarding sustainability or impact of solid waste combustion, one aspect of waste management that most do agree on is that the current practice of landfilling non-stabilized waste is not sustainable.

While a number of studies have characterized emissions from individual alternative thermochemical waste conversion processes, there is a lack of comprehensive and comparable data to make broad conclusions within technology categories. This is due to the wide variety of process configurations and control strategies that are uniquely applied to individual facilities. Most commercial facilities worldwide are evaluated on a case-by-case basis by regulatory agencies. Many existing conversion technologies in Europe and Japan must meet stringent regulatory standards. These standards are based on stringent policies adopted by the European Union and Japan. There are a number of studies that provide emissions data from processes that employ similar pollution control strategies to those used in alternative technologies. Some of this data is useful in predicting potential environmental impacts of California-based alternative waste conversion facilities. In addition, there are several alternative waste conversion sites currently under development in California. Measurements from these facilities are planned as these sites come on line, providing for objective independent verification of environmental performance.

The current practice of landfilling more than half of the solid waste stream in California carries environmental consequences that must be addressed, including air emissions, water quality, hazardous waste containment, and nuisance factors. Current information suggests that thermochemical and biochemical waste conversion processes can meet regulatory requirements and be operated in a manner that is comparable to other current industrial practices. That being said, properly-designed processes must address air emissions, solid waste residues, liquid wastes, nuisance factors, and risk factors.

5.1 Air Emissions

While biochemical processes have gained widespread acceptance for treating various feedstocks, thermochemical processes have met with resistance from the environmental community and the public. Some of this resistance has stemmed from the misperception that pyrolysis and gasification processes are variations of incineration or "mass burn." Another current misperception is that modern MSW combustion facilities are hazardous or emit uncontrolled amounts of toxic air substances. MSW combustion facilities in the U.S. currently emit about 12 g/year TEQ of dioxin/furan, compared with more than 4200 g/year TEQ in 1990. The industry represents less than 1% of the national dioxin/furan air emission burden (see Tables 5-7 and 5-8). There are instances where the amount of dioxin present in the outputs (air, solid and liquid) of the combustion facility are less than that present in the feedstock. An important difference between combustion (incineration) and pyrolysis or gasification is that pyrolysis and gasification are intermediate processes that produce gaseous, liquid, and solid products that can be used in a wide variety of applications. As discussed in Chapter 4, gasification of coal and petroleum resources is used predominantly for the production of chemicals, fuels, and synthetic gases. Many pyrolysis processes are also optimized for the production of oils. In the case of chemical and transportation fuel production, the emissions from a direct process effluent can be reduced or avoided, although consideration must be given to the ultimate use of these products as they are used or combusted downstream. Nevertheless, emissions from transportation fuels would tend to be more dispersed rather than concentrated at a single site, which tends to raise environmental concern.

Although chemical and fuel production from gasification and pyrolysis is possible, the most prevalent processes for MSW applications utilize post-combustion of gaseous and solid products on-site for heat and/or electricity production. Post-combustion processes associated with thermochemical conversion technologies still differ dramatically from incineration in several key respects:

- The volume of output gases from a pyrolysis reactor or gasifier is much smaller per ton of feedstock processed than an equivalent incineration process. While these output gases may be eventually combusted, the alternative processes provide an intermediate step where gas cleanup can occur. Mass burn incineration is limited by application of air pollution control equipment to the fully combusted exhaust only.
- Output gases from pyrolysis reactors or gasifiers are typically in a reducing environment, and can be treated with different technologies compared with a fully combusted (oxidative) exhaust. Reactant media can also be hydrogen or steam.
- Gasification and pyrolysis produce intermediate synthesis gases composed of lower molecular weight species such as natural gas, which are cleaner to combust than raw MSW
- Pyrolysis and gasification processes use very little air/oxygen or none at all.

These factors make control of air emissions less costly and less complex than that required for incineration.

While exhaust gas cleanup of thermochemical conversion processes may be easier than that associated with incineration, proper design of the process and emissions control systems is necessary to ensure that health and safety requirements are met. The output gases of pyrolysis and gasification reactors, and the subsequent combustion of the gases can contain a variety of air pollutants that must be controlled prior to discharge into the ambient air. These include particulate matter (PM), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), dioxins and furans, hydrocarbon (HC) gases, multiple metals, and carbon monoxide (CO). There are many strategies for controlling emissions from thermochemical conversion processes, and they are highly dependent on the process requirements of each individual facility.

Of particular concern in terms of potential environmental consequences are emissions of dioxins and furans, which are considered to be toxic. These compounds are formed under high temperatures when chlorine and complex mixtures containing carbon are present, and can be found in the gas and liquid phases. Dioxins and furans are typically formed downstream of the combustion process as the flue gases cool in a temperature range of 400-1290^{o} F, with a maximum formation rate at approximately 600° F. Combustion conditions that enhance the downstream formation of dioxins and furans include poor gas-phase mixing during combustion, low combustion temperatures, incomplete combustion of carbon species, and high PM loading. Molecular oxygen in the gas stream is essential for dioxin and furan formation via de novo synthesis, which is a formation mechanism that involves reactions with fly ash in the flue gas.[158]

The absence or reduction of oxygen in pyrolysis/gasification reactions inhibit dioxin formation in this regard. Chlorine is a critical component for the formation of dioxins and furans, although studies of chlorine levels in the feedstock have shown mixed results, with some studies indicating that higher chlorine levels in the feedstock contribute to dioxins and furans, while others do not.[159] For studies that have shown correlations between dioxins and furans and chlorine, the correlation is typically only observed at levels above 1-2% in the feedstock.

It is clear that proper design of thermochemical conversion processes and pollution control equipment is critical to addressing the risks associated with these dioxins and furans. A design element is to limit the amounts of chlorine and copper in the feedstock to minimize potential formation. In cases where this is not feasible, cold-quenching and/or high-temperature incineration of intermediate products is recommended to prevent release to the atmosphere. In cold quenching, intermediate gases are quickly cooled in a caustic scrubber solution in order to prevent the de novo synthesis of dioxins and furans. Alternatively, or in addition to cold-quenching, high-temperature incineration of intermediate gases can prevent de novo formation and destroy dioxins and furans already present. High-temperature incineration is, in fact, the recommended treatment for landfill gas collection systems.

Contaminant removal from the exhaust stream is typically accomplished with a variety of technologies described in Table 5-1. As noted above, thermochemical conversion processes may employ air pollution control at the reactor outlet as well as the exhaust gas outlet.

Table 5-1. Air Pollution Control Technologies

Contaminant	Control Technology
Particulate Matter (PM) and aerosols	Inertial separation, Baghouse, Scrubbers, Electrostatic precipitators (ESP)
Volatile metals (vapor state)	Carbon filters (or condense to PM or aerosols and use PM separation techniques)
Dioxin/furans	Limit chlorine mass input in feedstock, Cold-quenching and/or catalytic/thermal combustion]
Carbon monoxide (CO) and Hydrocarbon (HC) gases	Process design, Catalytic/thermal combustion, Re-burning, Carbon filters
Oxides of nitrogen (NOx)	Flame temperature control Low NOx combustors, Fuel nitrogen management, Selective catalytic reduction, Water injection, Re-burning
Oxides of sulfur (SOx)	Limit sulfur mass input. Scrubber
Acid gases	Scrubber

Emissions results from alternative waste conversion processes are available in the literature and have been also been provided by technology suppliers. Care must be taken in examining these results, due to the unique nature of each facility and the associated emissions controls and the importance of independently verified data. Emission results from different facilities are provided in Table 5-2 for air pollutants, along with U.S. and German limits for incineration. In many cases, emissions data are presented in terms of concentrations in the exhaust gas rather than as emission factors (i.e., normalized to an input mass or output energy basis). Third party verification of the data was not obtained for many of the results in the tables. However, all of the information was obtained from facilities that were commercially operational at some point and hence subject to a permitting process which would have included emissions verification. Several factors provide some limitations in making direct comparisons with facilities that might be seeking a permit in California. Although some facilities would need additional controls for different pollutants not meeting the emissions limits, the data overall indicate that gasification and pyrolysis processes with the most advanced emissions controls should be able to meet conditions required to achieve a permit in California.

EPA Emission Factors

EPA AP-42 emission factors for “starved-air” MSW combustors[160] are widely cited as representative of pyrolysis/gasification processes, as many of these technologies use a limited amount of air or oxygen in their design. The basic design of a modular starved-air combustor consists of two separate combustion chambers, referred to as “primary” and “secondary” chambers. Waste is batch-fed to the primary chamber, which typically operates between 40%-60% theoretical combustion air. The waste is burned on grates or hearths, with typical residence times in the primary chamber up to 12 hours. Gases from the primary chamber are subsequently combusted in the secondary chamber, with typical excess air levels between 80% and 150%. While this process may represent certain types of pyrolysis and gasification processes, other designs use very little, if any, oxygen or air in the thermal process. Furthermore, the AP-42 emission factors show only control efficiencies for processes equipped with an electrostatic precipitator (ESP). ESPs are designed to remove PM and have been shown to have little effect in removing gaseous air pollutants. Other air pollution control technologies can be employed to reduce gaseous emissions, including cold-quenching, scrubbers, catalytic reduction units, and activated carbon filters. Therefore, consideration should be given to both the process operating characteristics as well as the specific air pollution control systems when developing emission factors.

Table 5-2. Emission Results for Various Pyrolysis/ Gasification Facilities/Technologies (mg/Nm^3 unless noted)

	PM	NO_x	CO	TOC	VOC	SO_2	H_2S	Dioxins/ furan (ng/Nm^3)	HCl	HF	Cd	Pb	Hg
US EPA limits	18.4	219.8	89.2			61.2			29.1		0.01533	0.1533	0.0613
German limits (17thBImSchV)	10	200	50			50		0.10	10		0.03	0.50	0.03
Brightstar*	1.6-10	40-96	440-625		0.05	<0.1	<2	0.0331	<1.0	0.59	<0.0002	0.0051	
Compact Power†	0.11	26.49	7.13		0.49	3.37			0.17				
GEM‡	3	262	8		6	79		0.02	4	ND	ND		ND
Mitsui Babcock§ (Yame Seibu)		75 ppm	5 ppm			8 ppm		0.016	9 ppm				
Mitsui Babcock (Toyohashi)		<35 ppm				<10ppm		<0.005	<31 ppm				
PKA**	2.3	54	38	2.3		7.7		0.02	2.3	0.15	0.002		0.002
Pyromex††	1	135	38	0.5		20		0.005	1	0.03			
Serpac‡‡	4.2-5.2	61-189	0.5-2.5	0.2-0.5		0.0-5.6		0.002	1.7-5	<0.1			0.05
Technip§§	3	180	10	2		5		0.001	5	ND	0.02		0.02
Thermoselect*** (Karlsruhe)	0.84	21.76	2.95			0.16		0.0007-0.0011			0.001	0.013	0.0018
Thide-Eddith†††		470	50	<15		<200			30	<1			
Thide (Nakaminato)	<3		<20			<4		<0.01	<10				
TPS‡‡‡	3-7	200-300	2.5-5			5-15		0.013	0.6-2	<0.1	<0.004	0.005	0.008-0.05

Notes: PM = particulate matter, TOC=total organic carbon, VOC=volatile organic carbon, Cd = Cadmium, Pb=Lead, Hg=Mercury, ND=not detect, most values corrected to 11% O_2 on a dry basis

* Trip Report- Brightstar Environmental, Report by Malcolm Prinie, Ft. Lauderdale, FL, November, 2001, www.prinie.com
† Emissions results for 2/19/04 available at www.compactpower.co.uk.
‡ Heermann, C., F.J. Schwager, et al., *Pyrolysis & Gasification of Waste: A Worldwide Technology and Business Review*, Juniper Consultancy Services LTD., 2001.
§ Bryce, W.B. and Livingston, W.R., The Current Status of Mitsui R21 Process for the Advanced Thermal Processing of Municipal Solid Waste, Mitsui Babcock, Renfrew, Scotland.
** Heermann, C., F.J. Schwager, et al., *Pyrolysis & Gasification of Waste: A Worldwide Technology and Business Review*, Juniper Consultancy Services LTD., 2001.
†† Information provided by Innovative Logistics solution-Pyromex (probably for sludge system).
‡‡ Information from Serpac Environment website, www.bseri.com
§§ Heermann, C., F.J. Schwager, et al., *Pyrolysis & Gasification of Waste: A Worldwide Technology and Business Review*, Juniper Consultancy Services LTD., 2001.
*** Materials provided by Thermoselect licensee Interstate Waste Technologies, Inc., Malvern, PA.
††† Heermann, C., F.J. Schwager, et al., Juniper Report. Nakaminato data provided by Thide.
‡‡‡ Heermann, C., F.J. Schwager, et al., *Pyrolysis & Gasification of Waste: A Worldwide Technology and Business Review*, Juniper Consultancy Services LTD., 2001.

Case Studies

Waste Gasification

An example of a mid-process air pollution control system is the Thermoselect process, a high temperature gasification technology.[161] The company currently has four facilities in commercial operation worldwide, and three others under construction.

In the Thermoselect process, the crude synthesis gas exits the gasifier at approximately 2200° F and flows into a water jet quench where it is cooled instantaneously to below 200° F. The shock-like cooling prevents the formation of dioxins and furans by dramatically reducing the residence time of the synthesis gas at high temperature. Entrained particles (such as elemental carbon and mineral dusts), heavy metals, chlorine (present as HCl), and fluorine (present as HF) are also separated out in the quench. The pH of the quench water is maintained to a setpoint of 2 to ensure that heavy metals are dissolved as chlorinated and fluorinated species, and thus are washed out of the crude synthesis gas.

Following the quench process, the synthesis gas flows into a demister and alkaline scrubbers, where the remaining particulates and HCl/HF droplets are removed. The gas then passes through a desulfurization scrubber for the removal of H_2S by direct conversion into elemental sulfur. The scrubber is a packed bed that is sprayed with a scrubbing liquor consisting of water and dissolved iron that acts as a binding agent. The binding agent oxidizes the H_2S to elemental sulfur and water. Finally, the gas is dried in a countercurrent packed bed scrubber using a tri-ethylene glycol liquor. The fully-cleaned synthesis gas is then conveyed to engines for electricity production.

While information regarding air emissions from alternative thermochemical conversion processes of MSW is somewhat limited, other applications of air pollution control strategies have been better characterized. Information from these sources can provide a useful blueprint in application to alternative waste conversion. Examples include coal gasification, hazardous waste pyrolysis, and waste incineration air pollution control technologies. Some of the details of all of the steps in emissions control for coal gasification are provided in Appendix J.

Small Batch-Run Hazardous Waste Pyrolysis

Another example of a related commercial system is a pyrolysis technology applied to hazardous waste.[162] One such unit was described in comments to the U.S. EPA with regard to development of Maximum Achievable Control Technology Standards for hazardous waste incinerators.

The example technology processes both hazardous and non-hazardous waste generated from a tar product distribution center as well as related wastes from offsite sources. The heat from the incinerator exhaust gases are recovered and used to generate steam to support the plant's operations as well as an adjacent plant. The pyrolyzer is operated approximately 25% of the time. About 60% of the waste burns are hazardous. When treating hazardous waste, the facility operates under a RCRA Part B permit. When operating in a non-hazardous mode, the unit is governed by an air operating permit issued by the local air pollution control district.

The technology consists of two primary components: a batch pyrolysis furnace and a fume incinerator. Initial waste treatment involves a two-stage batch process, pyrolysis of the solid material followed by incineration of the off-gases. The pyrolyzer is first loaded with waste material. The unit is then completely sealed, so that no waste material or combustion products may exit except through the fume incinerator. An automatic 24-hour cycle is then initiated.

During this time, conditions are varied to heat- up, volatilize, burn out, and cool down the waste. Pyrolyzer gases are drawn through the fume incinerator that maintains high temperatures and provides combustion air and turbulent mixing required for thorough destruction (>99.99%). Pyrolysis occurs until all volatiles are removed from the waste feed batch. At the end of the devolatilization period, the air flow to the pyrolyzer is increased and the unit then functions as an oxidizer. The oxidizing atmosphere causes the carbon that remains after devolatilization to rapidly oxidize. The burnout period is over when the pyrolyzer temperature begins to drop, indicating that the carbon formed during the devolatilization period has been completely oxidized. Air flow to the pyrolyzer is continued until the furnace is cool enough to open for removal of the ash and preparation for a new waste batch.

The unit is operated to control air emissions using measurements of operating conditions, including but not limited to, continuously monitored combustion temperatures, combustion gas velocities, stack gas concentration of carbon monoxide, and interlock systems and analysis of the waste feed batches and limitations on the amounts of various components in the feed, e.g. metals, chlorine, etc. Each unique batch of waste is analyzed and custom blended using a computer program to ensure compliance with all batch limits. In combination with the combustion operating parameters and monitoring provisions, compliance with emission limits is assured. The emission limitations and feed batch limitations were developed based on site specific modeling and assuming 0% collection efficiency. Acceptable ambient concentrations were utilized to establish the maximum allowable emission rates. Individual batch weights and the amount of hazardous waste treated per quarter are strictly limited. Finally, the types of waste allowed to be incinerated are restricted to specifically identified coal tar products and/or related wastes with similar characteristics and constituents.

Tables 5-3 and 5-4 present the results of stack testing of various industrial facilities overseen by the Ohio Environmental Protection Agency. Table 5-5 presents total toxic emissions from similar testing conducted in South Carolina.

Table 5-3 Emissions Comparison of a Hazardous Waste Incinerator to other Industrial Process Emissions

Emissions (tons per year)			
Type of Company	Particulates	NOx	SO_2
Electric Power Plant	465	16,907	80,825
Cement Kiln	370	632	2,896
Steel Plant	310	1,643	42
Automotive Manufacturer	43	124	298
Hazardous Waste Incinerator	6	75	N.D.

Data source: US Environmental Technology Center, "Report on Combustion," 1999

Table 5-4 Emissions of Dioxins/Furans

Source	Dioxin/furan emissions (parts per billion)
Home electrostatic precipitator	1.0
Home fireplace soot	0.4
Diesel truck muffler	0.023
Automobile muffler	0.008
Hazardous Waste Incinerator	0.0000015

Data source: US Environmental Technology Center, "Report on Combustion," 1999

Table 5-5 Total Toxic Emissions

Source	VOC'S EMISSIONS (POUNDS PER YEAR)
Chemical Plant	3,551,921
Papermaking Plant	1,012,690
Textile Plant	155,434
Hazardous Waste Incinerator	156

Data source: US Environmental Technology Center, "Report on Combustion," 1999

A final example is the application of state-of-the-art air pollution control equipment on existing MSW incinerators. Baseline emissions testing was conducted at all 167 large MSW incinerator facilities in the United States in 1990. Consistent with Section 129 of the Clean Air Act, large MSW incinerators were required to retrofit their facilities with Maximum Achievable Control Technology by December, 2000. Subsequent emissions testing at all facilities was conducted to verify performance. Table 5-6 illustrates the dramatic improvement in emissions control following the retrofits.

Table 5-6 Emissions from Large MSW Incinerators

Pollutant	1990 Emissions	2000 Emissions	Percent Reduction
Dioxins/furans, total mass basis	218,000 g/yr	679 g/yr	99+
Dioxins/furans, Toxic equivalent quantity basis	4,260 g/yr	12.0 g/yr	99+
Mercury	45.2 tpy	2.20 tpy	95.1
Cadmium	4.75 tpy	0.333 tpy	93.0
Lead	52.1 tpy	4.76 tpy	90.9
Particulate matter	6,930 tpy	707 tpy	89.8
Hydrochloric acid	46,900 tpy	2,672 tpy	94.3
SO_2	30,700 tpy	4,076 tpy	86.7
NO_x	56,400 tpy	46,500 tpy	17.6

Source: United States Environmental Protection Agency Memorandum, "Emission from Large MWC Units at MACT Compliance," June 20, 2002.

These emission reductions were achieved via a combination of sophisticated process control and technology improvements in air pollution control equipment. Common exhaust gas cleanup technologies include spray dryers, fabric filters, carbon injection, selective non-catalytic reduction, electrostatic precipitation, and duct sorbent injection. Many of these same control strategies can be directly applied to any fully combusted gas streams from gasification and pyrolysis conversion processes. One could reasonably expect equal or better emission control performance for properly designed conversion technologies.

For comparison purposes, Table 5-7 shows the major sources of dioxin-type compounds in the United States in 1995. Also included in this table are the emissions levels from MSW incineration in 2000 that show a reduction of over 99% in the 5-year period.

Table 5-7 National Emissions Inventory for Dioxins/Furans, 1995

Dioxins/Furans Source	1995 Emissions (g TEQ/yr)
MSW Incineration, air, 1995	1250
Backyard Refuse Barrel Burning, air	628
Medical Waste Incineration, air	488
Secondary Copper Smelting, air	271
Cement Kilns (hazardous waste burning), air	156.1
Sewage Sludge, land applied, land	76.6
Residential Wood Burning, air	62.8
Coal-Fired Utilities, air	60.1
Diesel Trucks, air	35.5
Secondary Aluminum Smelting, air	29.1
2,4-D, land	28.9
Iron Ore Sintering, air	28
Industrial Wood Burning, air	27.6
Bleached Pulp and Paper Mills, water	19.5
Cement Kilns (non-hazardous waste burning), air	17.8
Sewage Sludge Incineration, air	14.8
MSW Incineration, air, 2000	**12.0**

Source: United States Environmental Protection Agency 1995 Emissions Inventory for Dioxins and Furans (U.S. EPA 2001a).

The tables illustrate that MSW incineration accounted for approximately 60% of total dioxin/furan emissions in 1990. Since then, emissions from MSW incineration have moved from the top emissions source to well down the list, due mainly to the application of sophisticated pollution control technologies. Overall, these data show that emissions control from thermochemical processes in general, including incineration, is well established and hence conversion technologies with the most advanced emission control systems should be able to meet regulations at the level that would be established in California.

Biochemical Air Emissions

Emissions from biochemical systems include air emissions from the use of the biogas or ethanol product (usually reciprocating engine, vehicle, gas boiler, or flare), liquid emissions from excess process water and de-watering operations, and land emissions depending on how the solid digestates are used or disposed.

In addition, there can be fugitive gas and dust emissions that depend on control strategies, operational practices, and level of maintenance at a particular facility (e.g., enclosed receiving buildings with may have exhaust air treatment to minimize VOC and dust emissions from unloading and feedstock storage).

Emissions from use of Biogas

Emissions from the use of biogas are typical of combustion processes burning methane. Gaseous emissions include NO_x, SO_x, CO, unburned hydrocarbons, and particulate matter. If the biogas is consumed in applications other than simple flaring, the emissions should be offset by those that would have been created from the displaced fuel.

Depending on SO_x emission limits and/or concentration of H_2S in the biogas, gas cleaning to lower sulfur and moisture content prior to use in reciprocating engines may be necessary. Wet scrubbing is typical and iron catalyzed oxidation and biological fixed-film reactor gas scrubbing methods are also used for sulfur removal. In some cases, simple compression and cooling of the gas, a common moisture removal technique, is sufficient to lower sulfur content to a suitable level.[163] Elemental sulfur is eventually deposited and can be safely disposed.

Oxides of nitrogen (NO_x) are always produced to some degree when fuel is burned with air and can be emitted at high levels from uncontrolled reciprocating gas engines. NO_x emissions are usually the limiting factor for stationary power generation using reciprocating engines. Because of impurities in biogas such as sulfur, and in some cases siloxanes, catalytic converters for control of NO_x and unburned hydrocarbons are currently not used. Flaring biogas generally emits lower NO_x because temperatures are lower than those encountered in combustion chambers, but there is no recoverable energy. Lean burn, pre-stratified charge, and exhaust gas recirculation technologies are used for reducing NO_x emissions from this class of engine.

Table 5-8 displays the range of emissions achieved in practice for reciprocating engines operating on biogas in California. The emissions are from actual measurement of engines fueled by landfill gas or WWTP digester gas. The engines are all spark ignition and employed lean-burn or pre-stratified charge technology (for NO_x reduction). The smallest engine in the data set was 260 brake-horsepower (bhp) with a capacity of 195 kW. The largest was 4235 bhp with a capacity of 3.1 MW.

Table 5-8 Emissions 'achieved in practice' from reciprocating engines fueled by biogas in California[164]

	(g/bhp-hr)	(lb/MW-hr)
NO_x	0.31 - 0.6	1 - 1.9
VOC	0.05 - 0.54	0.16 - 1.7
CO	1.5 - 3.9	4.7 - 12.1
PM	NA	NA

Tables 5-9 and 5-10 show California Air Resources Board (CARB) recommended best available control technology (BACT) for reciprocating engine and gas turbine (<3 MW) distributed generation applications respectively. BACT emissions depend on the fuel type; waste gas or fossil fuel and class of prime mover (turbine or reciprocating). The higher emissions allowed for biogas applications mainly reflect the fact that use of catalytic converters with biogas fuel is difficult and is not in routine practice. The 'achieved in practice' emissions (Table 5-9) fall below the recommended BACT levels except for CO.

Table 5-9 CARB Recommended BACT emissions for reciprocating engines[165]

	'Waste gas' fired			Fossil fuel fired		
	(g/bhp-hr)	(ppmvd)‡	(lb/MW-hr)	(g/bhp-hr)	(ppmvd)	(lb/MW-hr)
NO_x	0.6	50	1.9	0.15	9	0.5
VOC	0.6	130	1.9	0.15	25	0.5
CO	2.5	300	7.8	0.6	26	1.9
PM	NA	NA	NA	0.02	-	0.06

‡ ppmvd – parts per million by volume dry - values are approximate for reciprocating engines

Table 5-10 CARB Recommended BACT emissions for gas turbines < 3MW[166]

	'Waste gas' fired (any capacity)			Fossil fuel fired		
	(g/bhp-hr)	(ppmvd)	(lb/MW-hr)	(g/bhp-hr)	(ppmvd)	(lb/MW-hr)
NO_x		25	1.25		9	0.5
VOC		-	-		5	0.1
CO		-	-		10	0.4
PM		-	-			

Carbon monoxide and PM emission requirements are generally met by biogas fueled engines or turbines.

VOC Emissions from Composting of Digestate

Volatile organic compounds (VOCs) are a large group of anthropogenic or biogenic organic compounds with relatively high vapor pressures. VOCs can be potential air pollutants, due to their malodorous and hazardous properties and contribution to tropospheric ozone. In addition, VOCs can contribute to global warming and stratospheric ozone depletion. VOCs are usually defined as the organic compounds (except methane) with boiling points less than 175° F, while semi-volatile compounds are the organic compounds with boiling points between 175° F and 350° F. [167]

Smet et al.[168] compared VOC and ammonia emissions from two different methods for biochemical treatment of biodegradable wastes. Source separated household and garden wastes (70% garden, 20% kitchen and 10% paper wastes) were treated by (a) standard aerobic composting with upflow aeration and (b) a combination of anaerobic digestion followed by aerobic stabilization of digestate. VOC and ammonia emissions were measured from each process. Assuming the biogas produced in the AD stage of treatment method (b) is flared or combusted in an engine, then the total volatile emissions for treatment (b) would come only from the aerobic stabilization portion of the treatment or 6% of those from treatment method (a) (i.e., 44 mg/ton from treatment (b) versus 742 mg/ton from treatment (a), see Table 5-11). Additionally, the partially stabilized digestate from the AD portion of the combined treatment requires about 1/10 the amount of air during the aerobic phase compared to the full aerobic treatment method (a), which requires a proportionately smaller fan and biofilter for final control. However, most of the volatile emission from treatment (b) was composed of NH_3 (> 500 mg per cubic meter) requiring ammonia scrubbing if the gas is to be passed through a biofilter prior to exhaust.

Table 5-11. Emissions for Different Biochemical Treatment Methods.

Emission Compound	Treatment (a)- Aerobic Composting Emission (g/ton)	Treatment (b)	
		Anaerobic Digestion Emission (g/ton)	Aerobic Stabilization Emission (g/ton)
Total VOC	590	217	3
NH_3	152	1.8	41
H_2S	nd	17	nd
Total Volatiles	742	236	44

Komilis et al (2004) found gaseous VOC emissions from all principal biogenic components of MSW compost.[169] Total VOC emissions measured ranged from 570 μg per dry kg for food waste and yard wastes (mixed at 22% and 78% by dry weight respectively) to 6060 μg per dry kg for mixed paper. A mixture to represent the biogenic fraction of MSW (mixed paper, food wastes and yard wastes) produced VOC emissions at the rate of 1200 μg per dry kg. The VOC emissions are not proportional to, or additive with, the ratio of organic materials in the waste mixture implying interactions occur among the different substrates. The only chlorinated VOC detected was 1,4-dichlorobenzene, and emissions varied depending on the substrate. Komilis et al (2004) contains a good review of VOC emissions from MSW and composting operations.

Landfill Gas Emissions

An evaluation of the emissions impacts of conversion technologies would not be complete without a discussion of landfill gas emissions, which represent the current state of waste disposal. As discussed above, the bacterial decomposition of biogenic landfilled material produces significant quantities of landfill gas, which is composed of approximately 50% methane and 50% carbon dioxide. The methane emissions from landfills are particularly important, since methane is more potent as a greenhouse gas than carbon dioxide and since landfills represent the second largest source category of anthropogenic methane emissions behind the energy industry (see Table 5-18).

Tables of national methane emissions from landfills for 1990 to 2002 are presented on a total mass basis in Table 5-12. These tables show increases in total methane emissions created by landfills, but corresponding increases in landfill gas recovery leading to about a 10% reduction in net methane emissions to the atmosphere. A majority of the landfill gas produced by active landfills in the state is converted to electricity, and comparisons of electrical capacities provide a good comparison of the level of control of methane emissions from landfills in the state. As discussed in Chapter 3, landfill gas that is used for electricity production, is planned for electricity use, or is flared represents approximately 305.5 MW_e, while uncontrolled or vented landfills have a capacity of 31 MW_e. An additional 2750 landfills are no longer in use, and must also be accounted for.

Table 5-12: CH_4 Emissions from US Landfills (Gg)[170]

Activity	1990	1996	1997	1998	1999	2000	2001	2002
MSW Landfills	11,599	13,520	13,802	14,047	14,385	14,659	14,954	15,221
Industrial Landfills	812	946	966	983	1,007	1,026	1,047	1,065
Recovered								
Gas-to-Energy	(824)	(1,360)	(1,618)	(1,938)	(2,177)	(2,376)	(2,630)	(2,748)
Flared	(478)	(2,059)	(2,390)	(2,692)	(2,750)	(2,764)	(3,146)	(3,325)
Oxidized[1]	(1,111)	(1,105)	(1,076)	(1,040)	(1,047)	(1,055)	(1,022)	(1,021)
Total	9,998	9,942	9,685	9,360	9,419	9,491	9,202	9,192

Note: Totals may not sum due to independent rounding.

CO_2 Emissions

Another issue to consider is greenhouse gas emissions, including CO_2 emissions, and the Kyoto Protocol limitations on greenhouse gas emissions. One important method in reducing equivalent greenhouse gas emissions is through the use of renewable resources for energy production. As discussed in Chapter 1, in response to the Kyoto Protocol, the EU is implementing policies that incorporate the use of energy produced from renewable sources. Under the EC definition, the "biodegradeable fraction of industrial and municipal waste" is considered renewable. Facilities generating electricity using both renewable and none renewable energy source are provided credit for only the portion of the feedstock that is renewable.

5.2 Solid Residues

Essentially all conversion technologies will produce a solid residue because all components of the solid waste stream contain inorganic material (or ash). The amount of ash varies with the material and how it's handled before it becomes a conversion technology feedstock. Depending on markets and hazardous content of solid residue it may find commercial use or may need to be disposed in standard or hazardous waste landfills.

5.2.1 Thermochemical Conversion Solid Residues

All organic matter including biomass and waste contains trace quantities of heavy metals. Whether biomass or waste is landfilled, composted, gasified, combusted or incinerated, the heavy metal quantity remains identical; the only difference is that thermal decomposition processes retain most of the heavy metals in their residue/ash in a concentrated form. More volatile heavy metals will enter the gas phase in thermal conversion and must be managed or captured before exhaust to atmosphere. Conversion technologies, including incineration, do not generate heavy metals in ash but do concentrate heavy metals already present in the feedstock that would otherwise be landfilled. With proper management, the concentrated heavy metals can be treated and disposed of in a controlled manner that poses no greater environmental threat than landfilling. In some cases, metals may even be reclaimed from the solid residue.

Regardless of the process used for waste resource management, the amount of heavy metals contained in the feedstock itself primarily determines the metals concentration in the process emissions. For any given application, removing the main source of heavy metals is the most effective method for minimizing the level of trace heavy metals.

Any claim by suppliers that a particular waste resource management process can eliminate or produce fewer trace heavy metals is not factual, though residues from varying processes can have different leachability levels and trace metals partitioning to air, solid, or liquid residues may vary.

The char and ash from thermochemical processes contains trace heavy metals. Leachability characteristics, as shown in Table 5-13, are typically below the test limit. Normally these residues are classified as "Non-Hazardous" and "Non-Specialist" under UK, EU and US regulations. Metals content/leachability values for various technologies are provided in Table 5-14. In many processes, the ash is vitrified by heating above the melting point or fusion temperature of the ash. This slag is a hard glassy substance that has little if any leachability. The bottom ash and slag may also be used in different construction and other applications. A small amount of solid waste residues are generated by baghouse filters and scrubber solids, which must be periodically cleaned.

Table 5-13. EPA Leachability Limits for Non-Hazardous Waste

ITEM	METAL (*)	US / EPA TCLP Test Limit (mg/L)
1	Mercury (Hg)	0.2
2	Cadmium (Cd)	1.0
3	Thallium (Tl)	Not Applicable
4	Arsenic (As)	5.0
5	Lead (Pb)	5.0
6	Chromium (Cr)	5.0
7	Copper (Cu)	Not Applicable
8	Nickel (Ni)	Not Applicable
9	Zinc (Zn)	Not Applicable
10	Boron (B)	Not Applicable
11	Barium	100.0
12	Selenium	1.0

Source: USEPA Toxicity Characteristic Leaching Procedure (TCLP)
(*) Including compounds

Table 5-14. Ash Residuals and Leaching Data for Various Pyrolysis/ Gasification Facilities/Technologies (mg/l unless noted)

	Units	As	Ba	Cd	CN	Cr	Cu	Pb	Mn	Ni	Hg	Zn	All metals
BalPac	mg/l	0.05	0.37	0.1		0.01		0.58					
Compact Power	m/kg			4							0.1		289
Ebara/Alstom (glass granulate)	mg/l			<0.001	<0.01	<0.005	0.056	0.013		<0.01	<0.0005	0.05	
GEM	ppm	<100		<100		1330	406	<100	109		<100		
Nexus	mg/kg	<1		<0.05		<0.05		<1			<0.05		
PKA	mg/l	0.002		<0.001	<0.005	<0.01	0.072			0.014	<0.002	0.014	

Notes: As=Arsenic, Ba=Barium, Cd = Cadmium, CN=Cyanide, Cr=Chromium, Cu=Copper, Pb=Lead, Mn=Manganese, Ni=Nickel, Hg=Mercury, Zn=Zinc, ND=not detect

5.2.2 Biochemical Process Solid Residues

In general, biochemical conversion processes have the potential for much more solid residue than that from thermochemical processes. Biochemical conversion requires more time compared with thermochemical methods so practical systems are not large enough to convert all biodegradable components. This combined with the lignin components of biomass, which are not biodegradable in practical systems, plus the ash in the material results in substantial solid residue that may or may not have commercial use.

A major product possible from AD of MSW techniques is a compost or soil amendment that results from aerobic stabilization of the solid residue or digestate. If a compost market does not exist or adequate quality cannot be achieved then the solid residual may be used in thermochemical conversion or sent to landfill.

Compost quality consists of at least four aspects:

- Content of toxic compounds such as heavy metals.
- Absence of pathogens.
- Content of undesirable goods such as plastic, metal, glass etc.
- Plant nutritional value, i.e. inorganic nutrients as well as content of organic compounds for improving the structure and humus content of the soil.

Compost Quality – Heavy Metals

Composted digestate quality depends heavily on the quality or contents of the digester feedstock. Operators and regulations in Europe strongly encourage source separation of household and yard biogenic wastes from the “gray” or “rest” fraction for use in biochemical treatment for both improved digester performance and high quality or useable compost from the solid residue.

Heavy metals and other contaminates present in digester feedstock predominately end up in the solid digestate. Kubler et al. (2000)[171] reported that 80% of the heavy metals introduced into the digester (after pulping and separation of heavy and light fraction) were discharged to the solid digestate. The balance was not reported but presumably most of the remaining heavy metals were in solution in the process water. Metals concentration is generally higher in the digestate compared to that of the feedstock because of biomass conversion to biogas. Edelmann et al., (2004)[172] indicate that results from more than 1000 analyses of compost from anaerobic digestion with aerobic stabilization or just aerobic treatment of source separated biogenic fraction of MSW showed heavy metal concentrations less than half of the Swiss limits for compost (in ppm dry matter: Pb: 120, Cr: 100, Ni: 30, Zn: 400, Cu: 100, Hg: 1, Cd: 1).

Composted digestate quality and heavy metal concentration from operating commercial facilities in Belgium using the DRANCO AD process is reported on the Organic Waste Systems company website (http://www.ows.be/) and contained in a report by De Baere and Boelens (1999).[173] Table 5-16 displays some of these data. It includes detailed analyses of finished compost from the Brecht, Belgium plant, which feeds source separated household biogenic and yard wastes to a thermophilic high solids digester. The digestate is dewatered and composted in a covered facility with forced aeration. The finished compost meets the compost quality requirements for the

Flanders region in Belgium (Table 5-15). Data for heavy metals content for composted digestate from the Bassum plant is also shown in Table 5-15.

Table 5-15 Compost analysis from two DRANCO facilities in Belgium

	Units	Flemish Compost Standards	Average of Brecht Plant (source separated)	Bassum Plant (grey waste digestion) Fiber material		Sludge Fraction	
				Untreated	Treated	Untreated	Treated
Lead (Pb)	(ppm TS)	<120	97	80	60	220	90
Nickel (Ni)	(ppm TS)	<20	8	25	18	30	18
Zinc (Zn)	(ppm TS)	<300	180	350	180	900	250
Copper (Cu)	(ppm TS)	<90	32	100	55	240	80
Cadmium (Cd)	(ppm TS)	<1.5	1	0.9	0.5	1.9	1.4
Chromium (Cr)	(ppm TS)	<70	23	60	40	40	36

The feedstock used for digestion is the biogenic portion obtained from separation of the so-called "gray" or "rest" fraction of the waste stream. Gray waste is the remainder after recyclables, packaging, hazardous, and household biogenic waste fractions are source separated. About 60% of the gray waste stream becomes feedstock for the Bassum plant. Heavy metals content of the fiber and sludge fractions from composted digestate of a portion of the gray waste fraction is higher than that for source separated feedstocks. The compost from Bassum cannot meet the Flemish standards without first removing some of the heavy metals, especially zinc and copper.[174] Table 5-16 shows the metals content after a removal step at the back end of the digestion though the principles or technology used were not reported.

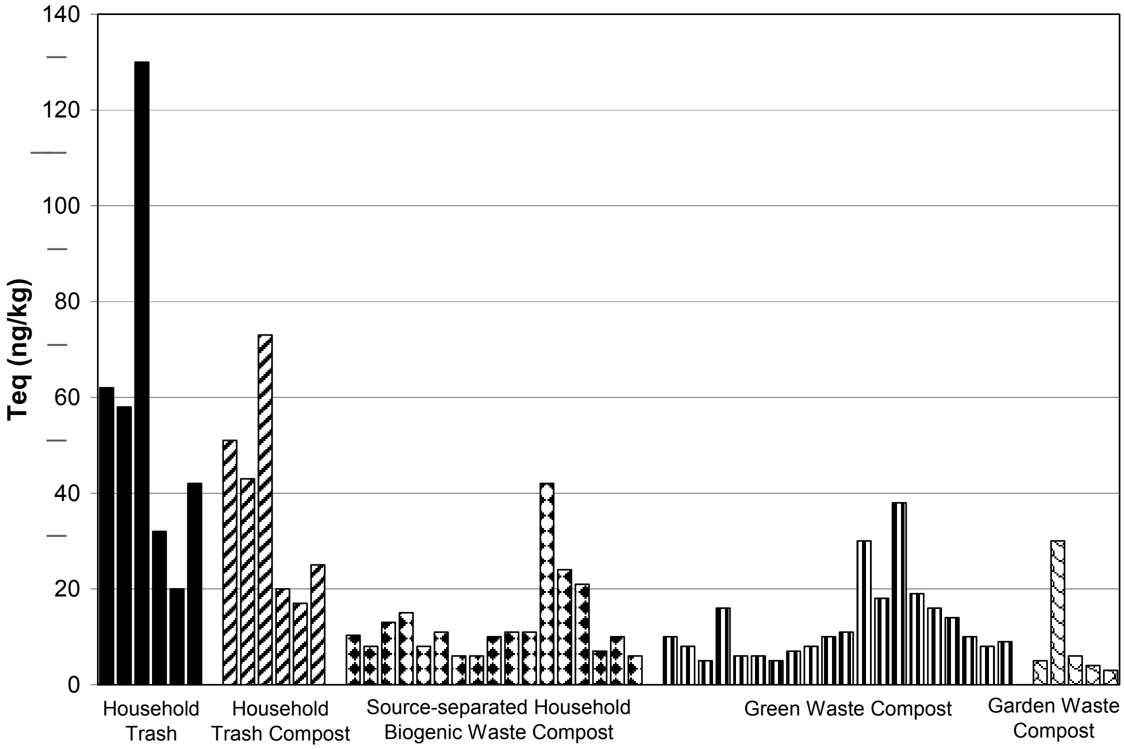
Kraus and Grammel (1992)[175] examined compost in several regions within Germany and observed that heavy metals content in compost of source separated biogenic fraction averaged 25% that of mixed MSW compost (Table 5-16). Most, if not all, of these compost samples were from raw or non-AD treated feedstock.

Table 5-16. Heavy Metal Content in Compost from Solid Wastes in Germany (Kraus and Grammel (1992))

Element	Mixed MSW Compost (ppm)	Source-separated Compost (ppm)
Lead (Pb)	420	83
Nickel (Ni)	84	26
Zinc (Zn)	919	224
Copper (Cu)	222	41
Cadmium (Cd)	2.8	0.4
Chromium (Cr)	107	61
Mercury (Hg)	1.9	<0.2

Dioxin in Trash and Compost

Further discussion in the detailed report by Brinton (2000)[176] of the Kraus and Grammel (1992) results reveals data from dioxin analysis of several types of compost and raw household solid waste from Germany (Figure 5-1). Averages from several samples of each category showed PCDD/F in raw household mixed waste was present in the amount of 57 ng/kg TEQ. Composted mixed MSW had PCDD/F levels of 38 ng/kg TEQ , followed by compost of source separated household waste with 14 ng/kg TEQ and about 10 ng/kg TEQ in green and garden waste compost. Brinton (2000) did not indicate whether the composted mixed household waste was from the same source as the raw mixed household waste or why the PCDD/F concentration was lower in the composted mixed house waste.



Note: Each column represents an individual sample.

Figure 5-1 PCCD/F content of raw household wastes and several compost types. (Source Kraus and Grammel (1992) as reported in Brinton (2000))

Pesticides and Herbicides in Compost and Composted Digestate

Certain man made pesticides or herbicides are known, or suspected, to persist in the environment after application. Clopyralid is a persistent herbicide used to control broadleaf weeds such as dandelions, clover and thistle. It is harmless to humans or animals but survives animal digestion and compost processes.[177] Clopyralid has been banned from certain uses in Washington after it was suspected of damaging tomato crops fertilized with compost. The chemical has been detected in some compost in California but no crop damage has been confirmed. In an attempt to limit use, (AB 2356, Statutes of 2002) requires clopyralid be sold only to qualified applicators.[178]

Other work has shown presence of chemicals and pesticides in household organic or biowaste.[179,180,181] Taube et al. (2002) examined samples of biogenic waste components of MSW crop protection products (CPP).[182] Typical household and yard wastes in Germany over a four-season period distributed between rural and urban sources were examined for more than 50 pesticide/herbicide chemicals. All samples contained CPP residues. Tropical fruit peels and residues had significant concentration of thiabendazole and methidathion, which are typically applied post-harvest for protection in transport and storage. Dimethoat, dodemorph, endosulfan and other fungicides were found in vegetable and garden wastes. Laboratory AD was carried out on raw samples and showed that some CPPs could be metabolized, modified, or otherwise stabilized to varying degrees. However, many are persistent (such as dodemorph) and can negatively affect plants and crops if the compost contains high enough levels.

5.3 Liquid Wastes

The liquid wastes generated by conversion processes include spent acid solutions from acid hydrolysis and liquid digestate from biochemical systems and spent scrubber solutions from the air pollution control equipment in thermal processes. There are well-defined mechanisms already in place for dealing with these waste streams. Generally, these waste streams are subjected to conventional chemical treatment processes. Products from the gas cleaning and water recovery processes include industrial-grade salts and a separate precipitate containing the heavy metals from the feedstock stream. In some cases, this precipitate may be rich enough in zinc and lead to warrant recovery in a smelter operation.

5.3.1 Thermochemical Process Liquid Residues

Oils created via pyrolysis can also contain toxic substances including acids, alcohols, aldehydes, ketones, esters, heterocyclic derivatives and phenols. Most of these compounds are used in current industrial operations. Thus, although these pyrolysis oils must be handled using appropriate precautions, they should pose no greater hazard than other industries where toxic substances are commonly used.

When feedstocks containing elevated levels of chlorine are used, chlorinated hydrocarbon species can be expected to be found in the pyrolysis products, unless a strongly reducing high-pressure hydrogen atmosphere is used to prevent their formation. Weber and Sakurai found that the pyrolysis of the residue from shredding industrial light bulbs and refrigerators resulted in the formation of PCDD/PCDF on the order of 1,500 to 10,000 ng/g in the pyrolysis oil.[183] These feedstocks were selected since they both have high chlorine and copper contents, both precursors to PCDD/F formation. The chlorine content of the industrial light bulb residue and the refrigerators were around 5% and 1%, respectively, while both materials contained a considerable amount of copper (3-6%). Of the PCDD/PCDFs formed, more that 90% of the toxic equivalent (TEQ) was found in the oil fraction. These researchers suggested that for the feedstocks and pyrolysis conditions investigated, the oils should not be utilized for further applications but rather thermally recycled on site. Mohr et al. also found levels of PCDD/Fs on the order of 1,983 ng/kg for input feedstocks containing 3,485 ng/kg PCDD/F in the input feedstock.[184] In some of the feedstocks tested, these researchers also found chlorobenzenes, chlorophenols, and PCBs, which they suggested could contribute in part to the observed PCDD/F levels. The overall Cl concentration in the feedstock was not provided, however. These researchers suggested that the pyrolysis oil should not be used as an energy source. Miranda et al. evaluated oils formed from the pyrolysis of commingled plastics containing PVC.[185] In this study, a sodium hydroxide scrubbing system was used to react with the HCl formed during the pyrolysis process, however. At pyrolysis temperatures of 680 °F, it was found that 99.84% of the Cl was volatilized. Using the scrubbing system, it was found that even with chlorine contents as high as 7.9 wt.% in the feedstock, Cl concentrations in the pyrolysis oils were found to be only 12 ppm. PCDD/F concentrations were not reported in this study. In summarizing these studies, the possible formation of PCDD/Fs and other chlorinated hydrocarbon species must be considered when dealing with high Cl-content feedstocks. This risk can be minimized by either direct hydrogasification, presorting out the Cl-containing materials in the waste stream, or utilizing a scrubbing system for HCl prior to condensing the pyrolysis vapors into an oil.

The environmental burdens associated with the conventional production of pyrolytic oils may exceed the economic advantages of low cost production from organic MSW. However, pyrolysis in a highly reducing atmosphere, does provide an option with low probability of forming chlorinated hydrocarbons.

5.3.2 Biochemical Process Liquid Residues

Process Water

Surplus water is usually generated from the MSW AD systems currently operating in Europe. Water quantity depends on the digestion technology as well as the substrate. In many instances, the liquid has a value as a fertilizer for agriculture application. Some compost operations can accept the liquid for use for compost moistening.

Table 5-17 shows the composition of the liquid fraction after separation of digestate solids from a "dry" thermophilic AD system (digesting source separated wastes). It is fairly high in nutrients and the heavy metals content is acceptable.

If there is no use for the surplus water, it needs to be treated and disposed properly. In some instances, nitrogen will need to be removed before disposal.

Table 5-17 Composition of liquid fraction from digestate after thermophilic AD. FM = fresh matter, DM= dry matter. (source Edelmann et al (2004))

General parameters	dry matter	org. matter	pH	C/N	NH_4-N	N-Min
13 samples	% FM	% DM			kg/t DM	kg/t DM
Average	14.2	44.8	8.2	10.2	11.24	11.25
Standard deviation	2.9	4.4	0.2	1.1	4.81	4.81

Macro-Nutrients	N-tot	P_2O_5 (tot.)	K_20 (tot.)	Ca (tot.)	Mg (tot.)
13 samples	kg/t DM	kg/t DM	kg/t DM	kg/t DM	kg/t DM
Average	21.0	12.8	31.6	36.4	9.7
Standard deviation	3.6	1.6	6.5	7.8	0.8

Heavy metals	Cd	Cu	Ni	Pb	Zn	Cr	Hg
13 samples	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM
Average	0.62	77.9	28.2	59.5	269.7	36.7	0.18
Standard deviation	0.10	6.3	6.7	21.9	29.0	8.2	0.06

5.4 Overall Environmental Impact of Anaerobic Digestion

For thermochemical and biochemical conversion processes, especially AD, the prospect of reducing methane and contaminated leachate emissions from landfills is probably the most significant environmental benefit. Treatment or conversion of the landfill stream and utilization of the products of conversion is more efficient than attempting to capture and use landfill gas. Global annual methane emissions are 239 and 359 million metric tonnes for natural and anthropogenic sources respectively.[186] According to 2002 data from the U.S. DOE, anthropogenic emissions of methane in the U.S. are estimated to be 26.6 million metric tonnes or 7.4 percent of global human derived methane. Table 5-18 shows U.S. anthropogenic methane emissions by major source category. The waste management category includes emissions from landfills (7.6 million metric tonnes) and domestic waste water treatment (0.7 million metric tonnes). Methane emissions from US waste management activities contribute 2.1% of the worldwide anthropogenic methane burden. .

Waste management operations or landfills account for 29%-37% of the U.S. anthropogenic methane burden (Table 5-18). The range is due to different methane emission inventories maintained by the federal government (USDOE or USEPA)

Table 5-18 Methane emissions in the US by source category for 2002

Source	Methane emissions (M metric tonnes)‡	(Tg CO_2 Eq.) ‡	(Tg CO_2 Eq.) [USEPA]*
Energy industry	10.95	230	203
Agriculture			
Livestock (enteric fermentation)	5	105	114
Animal wastes	2.48	52	40
Other (rice cultivation)	0.48	10.1	7.5
Waste management	7.61	160	222
Industrial processes	0.11	2.3	12
Total	26.6	559	598

‡US DOE http://www.eia.doe.gov/oiaf/1605/ggrpt/index.html
* US EPA , US Emissions Inventory
http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html

LCA Studies

Two recent papers that discuss LCA results for solid waste management scenarios were reviewed. One study compared results from four LCA methods for Korean mixed solid waste and practices with landfilling being the business as usual case.[187] The other study compared several current European solid waste treatment practices using a single LCA methodology.[188] The functional unit of waste in the Korean study was 1 ton of the complete mixed MSW stream whereas the Edelmann study used 10,000 tons of source separated household and yard waste (biogenic fraction of solid waste). The Edelmann study does not consider landfilling untreated biogenic solid waste in the LCA because the practice is banned in many countries of the EU and will likely be banned through out the EU in the future.

For the study in Korea, landfilling (with no LFG recovery) has the highest life-cycle environmental impact whereas combustion and anaerobic digestion (both with energy recovery) had the lowest (Figure 5-2). Open composting consistently ranked second highest in lifecycle impacts.*

* See below about cautions making comparisons to California facilities

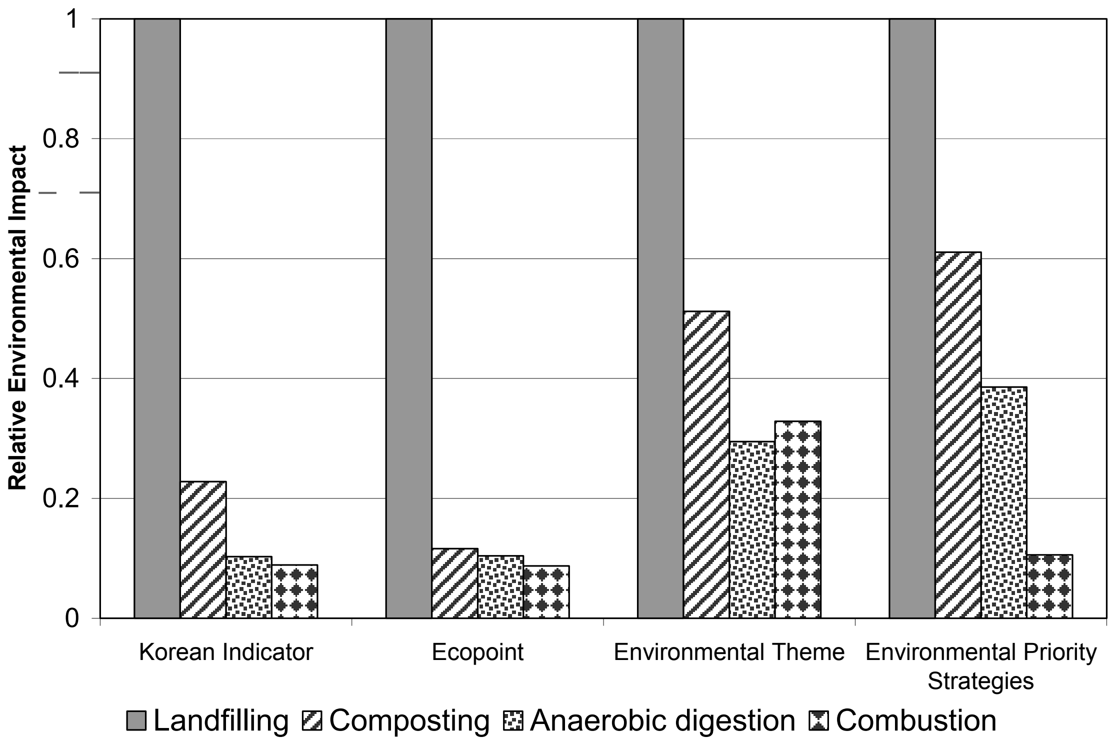


Figure 5-2. Results from Four LCA Methodologies (or LCIA for life cycle impact assessment) used to Compare Solid Waste Management Scenarios in Korea (adapted from Seo, et al. (2004)).

Impacts are based on equal amounts of "standard" Korean solid waste treated in one of four ways: (1) dry-tomb landfill with no collection of landfill gas, (2) composting with stabilized residue sent to landfill, (3) anaerobic digestion with energy recovery and stabilized residue sent to landfill, and (4) combustion with energy recovery and residue landfilled.

Environmental impact categories considered in the analyses were:

- Global climate change
- Stratospheric ozone depletion
- Acidification
- Eutrophication
- Abiotic resource depletion
- Photochemical oxidant creation
- Ecotoxicity to water emission
- Human toxicity to air emission

In each case, landfilling had the highest negative environmental impact due largely to global warming contribution (methane emissions) and water quality (toxicity and eutrophication effects).

Averaging the results from the four LCA methods, the landfill treatment method had three times the negative environmental impact as open composting, the method with the next highest impact. Recovery of LFG and energy production in the landfill scenario would reduce the negative impacts but would likely still be larger than the compost scenario.

In this analysis, composting has high impacts due to the relatively large amount of energy required for the process, some emissions of VOCs (including some methane created in anaerobic pockets of compost) and its effect on leachate after being landfilled. Using the compost in land application or soil amendment instead of putting in the landfill would likely reduce its overall impact.

Combustion with energy recovery ranked lowest in environmental impact in three of the four methodologies.

Anaerobic digestion with energy recovery and landfilling of the solid residue had very good overall environmental impacts in the study. It was ranked second lowest (in negative impacts) in three methods and lowest by one of the methods.

Caution should be used in generalizing these results for application in California. At least two important management practice differences in are likely to be used in California: Landfill gas would be recovered and flared or converted to energy, and some or all composted material would not go to landfill.

The study by Edelmann et al. (2004) used operating data from full size commercial composting and anaerobic digestion facilities in Switzerland.[189] The data for the combustion scenario was based on design data from the most recent facility being commissioned in Switzerland.

The LCA method use was EcoIndicator99 and incorporated more than 100 impact factors (materials and resource inputs and emissions). The impact categories were:

- Global climate change
- Stratospheric ozone depletion
- Acidification
- Eutrophication
- Heavy metals
- Carcinogens
- Pesticides
- Photochemical oxidant creation
- Ecotoxicity to water emission
- Human toxicity to air emission

The options evaluated included combustion with energy recovery, anaerobic digestion with energy recovery followed by aerobic stabilization of the digestate, and open composting with periodic windrow turning. The stabilized digestate and compost product were assumed to be land applied.

Figure 5-3 shows the relative environmental impact of three treatment options for the biogenic portion of solid waste. Open composting and combustion were nearly equal in terms of environmental impact. Landfilling untreated biogenic waste was not evaluated because it is generally no longer practiced in much of Europe. Anaerobic digestion had the lowest life cycle impact. Because the stabilized solid residuals from the two biochemical treatment types (open composting and AD) were land applied, then the relative impacts of the three treatment methods in the Edelmann study are more applicable to comparing to California for source separated biogenic fraction of household and yard wastes.

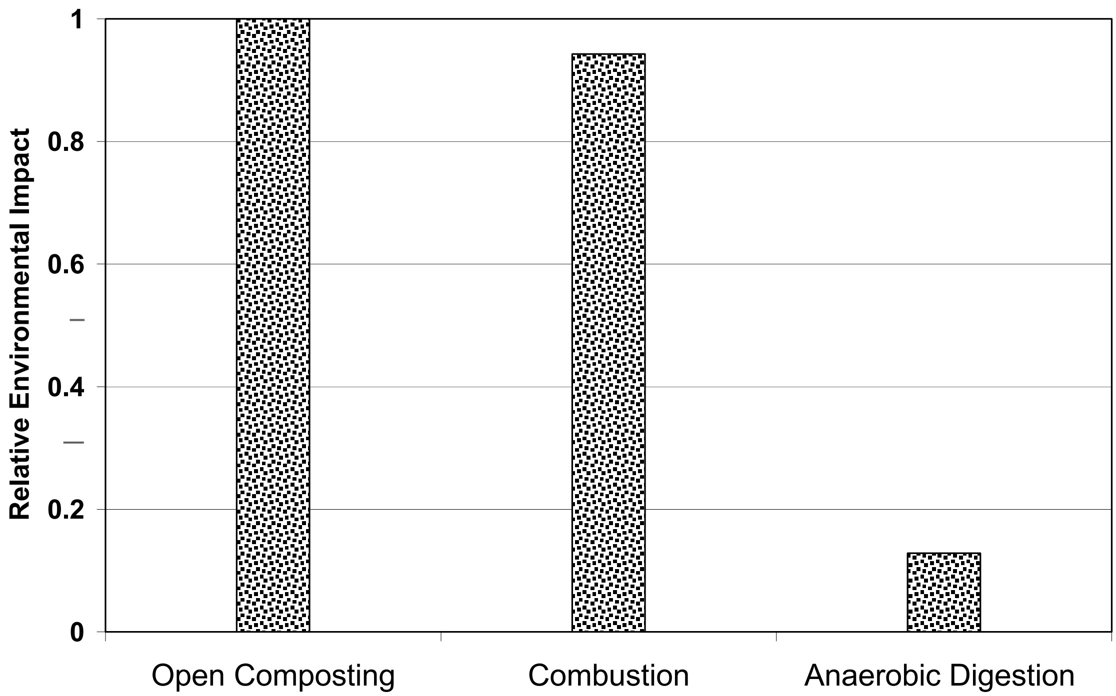


Figure 5-3 Relative Impact from Treatment Options for Biogenic Wastes for a Scenario in Europe (adapted from Edelmann et al. (2004))

5.5 Nuisance Factors

The nuisance factors associated with conversion technologies can include noise, odors, fugitive emissions, dust, litter and debris, increased local traffic, aesthetics, and animal and insect pests. In general these impacts would not be expected to increase and may be reduced compared with what is experienced in existing solid waste facilities. The use of engines, turbines, and generators to produce electricity may result in increased noise but this is commonly mitigated by enclosing the generating equipment. Conversion processes generally occur in an enclosed vessel so that odors, fugitive dust, and litter are not typically associated with the reactor component of the system. Co-location of conversion facilities at existing solid waste facilities will not result in any increased traffic because the existing transportation infrastructure can be used and material can be transported via conveyor belts. However, there may be some minor traffic impacts associated with offsite transportation of commercial products and byproducts for marketing and disposal.

5.6 Other Risks

Other risks associated with conversion technologies include potential acid spills in biochemical processes and leaks or breaches in high-pressure thermal conversion systems. It is expected that these risks can be adequately managed within the well-defined risk abatement mechanisms already in place for industrial processes.

5.7 Environmental Conclusions

From an environmental perspective, advanced alternative waste conversion technologies have several potential benefits over landfilling or even mass incineration. Existing facilities are operating within existing regulatory constraints. There are no “one size fits all” regulations on pyrolysis and gasification systems due to the wide range of process parameters, end-use of products, and degree of air pollution control and are generally regulated on a case-by-case basis. The actual impacts of specific facilities would be evaluated as part of a local permitting process.

6 Discussion and Conclusions

Conversion technologies for MSW components are operating world-wide with most of the development and deployment occurring in Europe and Japan. A combination of dwindling landfill capacity, high tipping fees, increased environmental concerns, strict policy measures, high energy prices, and others have created a market for conversion technologies.

Adoption of conversion technologies in California will depend on public acceptance, improvements in economics and may require some adjustments in solid waste policies.

This section summarizes the main findings of the study and provides conclusions in areas such as potential for landfill reduction, technical viability, and environmental impact.

6.1 Landfill Flow Scenarios

6.1.1 Historical and Current California Landfill Disposal

Since implementation of the Integrated Waste Management Act, waste disposed in California landfills decreased from 44 million tons in 1989 to a low of about 35 million tons in 1996. Since 1996, landfill disposal has generally increased to 39.9 million tons in 2003.[190] The estimated waste diversion has steadily increased from 10 percent in 1989 to 47% in 2003. Population has increased from 29.4 to 35.6 million people during the same period which equates to an average annual increase of 1.3% and is expected to continue increasing reaching 45.5 million by 2020 and 58.7 million by 2040.[191,192] This continued increase in population will continue to burden the infrastructure in California, including that for solid waste management.

A surprising trend is evident for waste generation and disposal amounts viewed on a per-capita basis (see Figure. 6-1). The per capita disposal amount has remained fairly constant at 2200 pounds per person per year since 1995 while the estimated per capita waste generation has grown by 39% from its low of 3000 pounds per person per year in 1993 to 4250 pounds per person per year in 2003. These data are for all waste generation sources; industrial, commercial and residential. The increase in estimated diversion stems from an increasing per capita waste generation estimate and is not due to decreasing per capita disposal that is instead mostly unchanging.

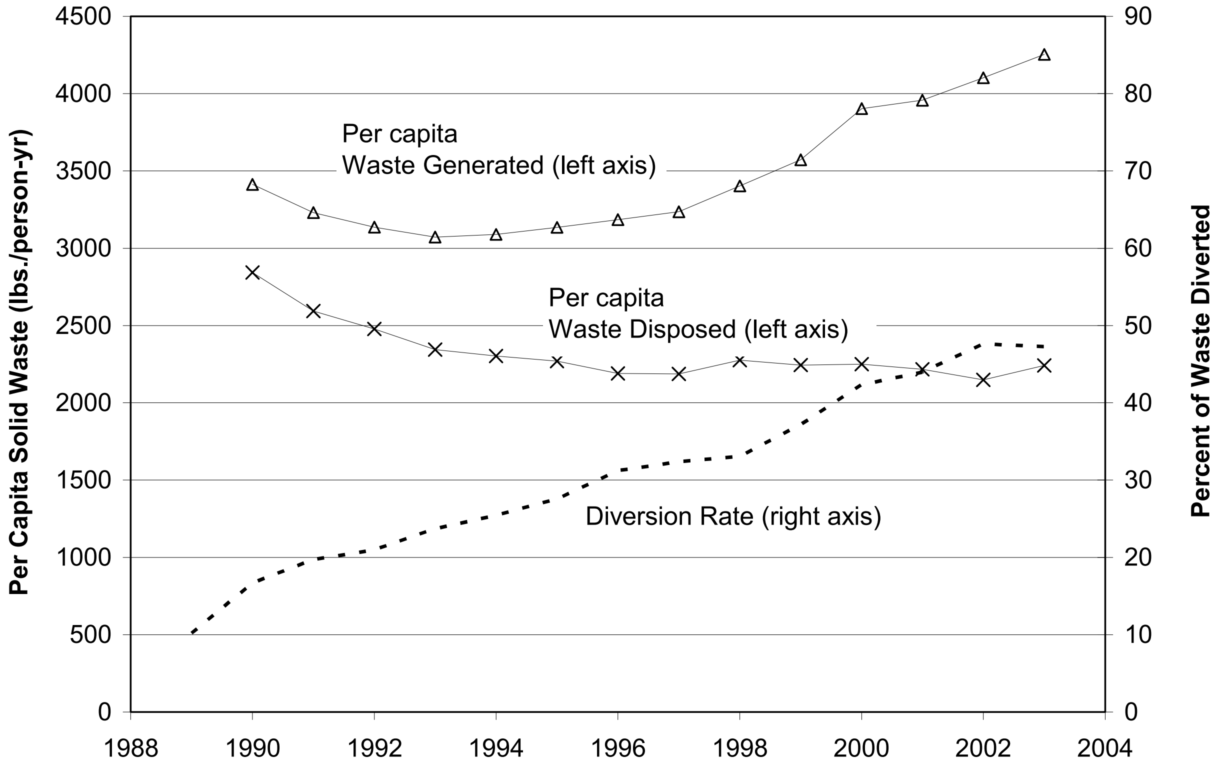


Figure 6-1 Per-capita waste generation and disposal in California with associated waste diversion rate (adapted from [193])

6.1.2 Landfill Flow Projections

If waste generation continues its upward trend and diversion rate remains at or near 50%, then per capita disposal amounts will begin an upward trend. This, combined with the growing population will sharply increase the landfill disposal amount over the coming years.[194] This is not sustainable in the mid to long term and will require a change in existing waste management policies and practices.

The current diversion rate approach to controlling landfill waste amounts may need to be revisited because per capita disposal has not declined in recent years. There seems to be an inherent disincentive for overall waste reduction in the diversion requirement approach because the waste generation estimate is used to set the upper yearly disposal limit for a jurisdiction to be in compliance and measuring waste generation is too complex and costly to accomplish on a regular basis. The higher the estimated waste generation amount, the higher the allowable disposal. In order to manage the affects of increased population on disposal amounts, reducing per capita disposal is a direct approach that is certainly measurable and is ultimately the only way to achieve a zero waste society. Measures that might work to this end include simply charging higher waste disposal fees, 'pay as you throw' fees, implementing extended producer responsibility (EPR) or 'producer pays' laws, or restrict total organic carbon (TOC) and/or bulk energy content of the material being landfilled. Many of these policies have been adopted and successfully implemented in Europe.

New uses and markets for the material currently landfilled should be developed as it is inefficient and burdensome to future generations to continue to landfill huge resources. Whether or not significant waste source reduction is implemented in California, very large waste streams are anticipated for at least the next 40 years and conversion technologies with the commensurate enhancement of recycling must be considered as a management option.

6.2 Process Summary and Discussion

Conversion technologies vary in their operational principals, variety of feedstocks to which they can be applied, and products. The primary processes reviewed in this report are thermochemical processes such as pyrolysis and gasification and biochemical processes such as anaerobic digestion, aerobic digestion, and fermentation. Plasma arc or catalytic cracking are two additional subcategories of thermochemical processes that were reviewed. A summary of the process and performance characteristics is provided in this section as it relates to the evaluation criteria being used for this report.

Table 6-1 provides a summary of the overall performance, process characteristics, and products for each of the surveyed conversion technologies.

Table 6-1 Process Characteristics for Various Conversion Technologies

Conversion Technology	MSW component processed	Energy Efficiency	Products Mole %	Scale – Commercialization (energy output)
Partial oxidation gasification air-feed (a)	All organics low moisture <50% wet basis depending on reactor type	75% (cold gas)	29% CO 3% CO_2 15% H_2 3% CH_4 50% N_2	0.5 to 5 MWt
Partial oxidation gasification oxygen-feed (b)	All organics low moisture <50% wet basis depending on reactor type	90% (cold gas)	18% CO 30% CO_2 40% H_2 9% CH_4 1% N_2	5 to 150 MWt
Indirectly fired gasification (c)	All organics high moisture or dry	85% (cold gas)	15% CO 9% CO_2 59% H_2 14% CH_4 3% N_2	10 to 25 MWt
Hydro-gasification with steam pyrolysis (d)	All organics high moisture or dry	90% (cold gas)	11 % CO 24 % H_2 6 % CO_2 49 % CH_4	Pre-commercial
Indirectly fired Pyrolysis with drier & gasifier	All organics high moisture or dry	65% (cold gas)	7% CO 40% CO_2 5% H_2S 32% H_2 15% *HCs*	0.5 to 5 MWt

Conversion Technology	MSW component processed	Energy Efficiency	Products Mole %	Scale – Commercialization (energy output)
Indirectly fired Pyrolysis with drier (e)	All organics high moisture or dry	55% (cold gas)	5% CO 36% CO_2 3% H_2S 19% H_2 36% *HCs*	0.5 to 2 MWt
Anaerobic Digestion	Biodegradable Components	30-60% (cold gas)	40-60% CH_4 60-40% CO_2	0.1 to 10 MWt
Fermentation (f)	Biodegradable Components	30-70% (liquid)	Ethanol	0.1 to 10 MWt
Aerobic Digestion (Composting)	Biodegradable Components	N.A.	Soil amendment	N.A.

Table notes

(a) Foster-Wheeler, Fluidized Bed, steam/air
(b) Lurgi, Dry ash Entrained Flow, steam/oxygen; Fully commercial for coal and petroleum coke, including uses where MSW is cofired with these feedstocks.
(c) COGAS, Fluidized Bed, Indirect Heat, Probstein & Hicks (1990); commercialization is demonstration scale for biomass feedstocks.
(d) Hydrogasifier design C, Probstein & Hicks (1990)
(e) Baughman et al., Synthetic Fuels Data Handbook, Cameron Engineers, 2002
(f) Fully commercial for sugar and starch and pre-commercial for cellulosic feedstocks

6.2.1 Thermochemical Conversion Pathways

The evaluation of alternative thermochemical conversion technologies indicates that these technologies can be successfully applied to the processing of MSW. Alternative thermochemical conversion technologies vary depending on the broader categorization (i.e., pyrolysis vs. gasification), as well as the individual process design. Gasification systems can provide some additional flexibility in the production of different products since the process includes a reaction step, but can have additional complexity. The efficiencies of gasification and pyrolysis technologies vary considerably depending on the technology, specific feedstocks being processed, and the products produced. Similarly, the extent of air pollution control equipment employed by a specific technology or facility is probably the most critical element in maintaining emissions within regulatory limits.

Both pyrolysis and gasification are already being utilized for MSW in other parts of the world, where permitting and other requirements similar to those in California are in place. Installed world-wide capacity of non-combustion thermochemical conversion of MSW is more than 2.5 million tons per year, which is slightly less than 8% of the total organic material landfilled in the state. Approximately 50 facilities using either pyrolysis or gasification to process MSW commercially were identified. This includes several facilities that have been operating on MSW for between 10 and 30 years. Although some processes/facilities have experienced operating problems, and the technologies are not fully mature for MSW or other heterogeneous feedstocks, the availability and number of more advanced operating facilities/technologies indicates that these technologies could provide a near to longer term solution to reduction of organic material to landfill.

6.2.2 Biochemical Conversion Pathways

Systems for anaerobic digestion of MSW components have been under development for many years. Successful deployment of AD conversion systems has occurred mostly in Europe, though there are some operating units (with more on order) in Asia, Australia, Israel, and Canada. In Europe, the installed capacity of AD conversion systems that digest MSW components has grown substantially in the past 15 years and is currently estimated to be 2.8 million tons per year which represents 9% and 7% of the total landfilled solid waste and organic (biogenic and plastics) disposal amount respectively.

Fermentation of biomass material into ethanol is fully commercial for sugar and starch based feedstocks such as sugar cane and corn. Cellulosic feedstocks, including the major fraction of organics in MSW, are more difficult to hydrolyze, requiring more extensive pretreatment. It is not yet commercial for cellulosic biomass and remains the subject of intense research. There are several facilities which use (or will use) cellulosic biomass for conversion to ethanol at either the demonstration, commercial scale construction, or commercial proposal stages.

6.3 Landfill Reduction Potential

The attributes of each conversion technology analyzed in this report to reduce the material deposition to landfill may be summarized in the following Table 6-2.

Table 6-2. Conversion Technology Summation

Conversion Technology	Portions of Waste Stream that can be processed	Carbon Conversion Efficiency to Products	Residual
Partial oxidation gasification air-feed	All organics, less Cl containing materials	40-60%	Ash (inorganic) Char, Metals
Partial oxidation gasification Oxygen-feed	All organics, less Cl containing materials	60-80%	Ash (inorganic) Char, Metals
Indirectly fired gasification	All organics, less Cl containing materials	70-90%	Ash (inorganic) Char, Metals
Hydro-gasification with steam pyrolysis	All organics, less Cl containing materials	80-95%	Ash (inorganic) Char, Metals
Indirectly fired pyrolysis with drier & gasifier	All organics, less Cl containing materials	70-80%	Ash (inorganic) Char, Metals

Conversion Technology	Portions of Waste Stream that can be processed	Carbon Conversion Efficiency to Products	Residual
Indirectly fired pyrolysis with drier	All organics, less Cl containing materials	50-60%	Ash (inorganic) Char, Metals
Anaerobic digestion	Biodegradable organics only	40-50%	Inorganics, metals, glass, undegraded biomass
Fermentation	Biodegradable organics only	40-50%	Inorganics, metals, glass, undegraded biomass
Aerobic digestion	Biodegradable organics only	40-50%	Inorganics, metals, glass, undegraded biomass

The waste stream as a whole contains approximately 80% organic material that can be processed using the range of conversion technologies discussed in this report. Of the technologies surveyed, the thermochemical processes can accept a broader range of feedstocks, and hence would likely provide a greater potential for landfill reduction than the biochemical processes if only a single process is implemented. Thermochemical conversion processes can potentially handle nearly all of the organic fraction of post-recycled MSW, although preprocessing such as shredding or drying would likely be used. Some additional components may also be excluded for environmental factors, as discussed below.

The biochemical processes are more limited than thermochemical processes in that they can process only the biodegradable components of the MSW feedstocks (i.e., most existing plastic components would not be biochemically converted). Higher moisture feedstocks tend to be good candidates for biochemical processes. The application of biochemical systems is best used for sorted green or food waste or certain components of a general MSW stream after sorting, such as office paper.

To maximize the utilization of the organic wastes currently being landfilled, some form of automated or manual presorting would be required prior to conversion. This sorting process would remove the metals, glass, paper, and plastics components that already have established markets for recycling. This additional processing should result in increases in recovery rates for recyclable materials.

Conversion technology residuals and feedstocks must be considered when evaluating the potential for reduction of material flow to landfill. For the thermochemical processes, the residual is primarily the non-reacting ash or mineral components of the waste. These could potentially be recycled or reused by metal or glass processors or as an aggregate in construction applications. Of the thermochemical processes, complete gasification generally maximizes the production of gas that can be used as a fuel or chemical feedstock and minimizes the production of char or carbon in the residues. For biochemical processes, the lignin components of the biomass feedstock as well as the mineral and plastics, comprise the solid residue. Lignin in the biomass components of MSW is essentially completely inert to fermentation and anaerobic digestion and becomes an organic byproduct that could be used as boiler fuel, or become a feedstock for general thermochemical conversion processes to produce other fuels and energy products. The solid residue from biochemical processes can be landfilled, de-watered and used in compost applications (if source separated or well sorting feedstocks are used), or post-sorting to recover metals, glass and plastic materials can be done before landfilling.

6.4 Environmental Impacts

Overall, it appears that the environmental impacts of thermochemical and biochemical processes can be minimized to provide no greater threat to human health or the environment than current waste disposal practices. Thermochemical processes are the most controversial due to perceived negative environmental impacts. Pyrolysis and gasification processes produce intermediate products that can be used for other purposes such as liquid fuels and chemicals. For close-coupled combustion of product gases, a review of emissions data suggests advanced thermal conversion technologies will be able to meet current emission standards. With reduced gas flow volumes in pyrolysis and gasification processes and better feedstock control, these technologies have the potential to meet even tighter emissions limits. Due to the wide range of process parameters, end-use of products, and degree of air pollution control, conversion technologies will generally need to be regulated on a case-by-case basis.

In applications where post-combustion of product gases occurs for heat and power production, advanced conversion plants being developed have inherently lower emissions than mass burn combustors and require less sophisticated pollution abatement. The lower emissions from conversion facilities in comparison with MSW combustion is due to several factors including: (a) lower gas flow won't entrain as much particulate matter and smaller emissions control equipment can be simpler to operate (b) emissions control is less costly per pound of feedstock treated compared with mass burn and (c) improved gas combustion (lower molecular weight components) (d) reaction media such as hydrogen or steam could be used in place of air or oxygen in certain processes.

6.5 Economic

The broad implementation of conversion technologies could affect the state economy in number of different ways, including the replacement of petroleum sources, increase in distributed electrical generation facilities, the introduction of products, the diversification of product markets, extension of landfill lifetimes, as well as the specific economic impacts related to the plant itself.

6.5.1 Resource Potential

As a resource, over 39 million tons of MSW is being buried in California landfills each year with over 78% of that material being organic. This represents an estimated chemical energy equivalence of over 60 million barrels of crude oil. At a market price of \$37 per barrel, this energy resource could be considered to be worth more than \$2.2 billion. Since most crude oil is refined to produce fuels and chemicals that have added values in excess of \$45 per barrel. The potential annual revenue from converting one half of all the organic materials that are being sent to landfill into marketable fuels and chemicals is over \$1.35 billion per year.

One resource component that may be particularly attractive for primarily thermochemical conversion technologies is the plastic component of MSW. Plastic and polymer organic materials contain over 30% of the chemical energy in California MSW, and are growing at a faster rate than that of biologically-derived organic materials. Conversion methods that can process this component of MSW could become increasingly more important, especially with the difficulties presently encountered attempting to recycle plastics and textiles.

6.5.2 Commercialization Potential of Conversion Technology Facilities

Landfilling solid waste will remain the least expensive waste management option for most of California as long as environmental and social costs are not attributed to the landfill. Most actively operating commercial-scale conversion technology facilities are located in Europe or Japan where markets and policies are much different than in California. At present, there are no fully commercial operating conversion technology facilities in California, although several are either being commissioned or are in the planning stages. In the near term, it is expected that jurisdictions faced with siting a new landfill or long transportation distances for their wastes will be the early pioneers of conversion technologies. For widespread adoption, markets, tipping fees, and solid waste policies will have to be more favorable.

Although the general degree of commercialization of the different conversion technologies can be partly assessed by evaluating facilities at various locations around the world, an economic evaluation of the facilities was not a part of this report. It was noted, however, that the level of commercialization for conversion technologies for MSW appeared to be largely, but not entirely, associated with niche markets where either public funds are used to offset capital and/or operating costs, specific feedstock and products distributions can be viable, or where landfill costs and energy prices are high. Given the economic competition with existing landfill operations, some public support may be required to advance conversion technologies. This could include assistance from a municipality or other government institution to offset capital and operating costs, increase the availability of feedstocks, or develop a market for the product(s). Conversion technologies may, in some cases, compete with recycling for similar feedstocks, although overall it is anticipated that recycling could increase. If California decides to restrict per capita disposal amounts or require waste treatment before landfilling, then existing recovery and recycle markets would benefit, waste reduction would become more important, and conversion technologies will develop.

6.5.3 New Products to Market

Products from conversion of MSW could have a large economic impact.. For example, as discussed in Chapter 4, the production of electricity by conversion of the waste stream could provide up to 8% of the State's current amount of electricity consumed.

Besides electrical or heat energy, the production of chemicals, fuels, and synthetic gases are possible with both thermochemical and biochemical processes. Such products are already commonly produced by gasification of coal and petroleum feedstocks. Products that can be created from the various conversion technologies are listed in Table 6-3. These include a range of liquid fuels and chemicals including methanol, Fischer-Tropsch diesel fuel, hydrogen, synthetic ethanol, or substitute natural gas.

Table 6-3. Products Available per Process Used

Conversion Technology	Primary Product	Secondary Products	Solid Residues	Value of secondary products	MSW component processed
Complete gasification	Synthesis gas	Fuels, chemicals and electricity	Ash metals recycle or landfill	Very high and flexible	All organics low moisture
Incomplete gasification (See pyrolysis)	Fuel and synthesis gas	Electricity, some marketable fuels	Char ash metals recycle	Moderate may need refining at additional expense	All organics low moisture
Hydro-gasification with steam pyrolysis	Synthesis gas	Fuels, chemicals water and electricity	Ash metals recycle or landfill	Very high and flexible Recycled water	All organics wet or dry
Indirectly fired pyrolysis with drier & gasifier	Fuel and synthesis gas	Electricity, some marketable fuels	Char ash metals recycle or landfill	Moderate may need refining at additional expense	All organics low moisture
Indirectly fired pyrolysis with drier	Fuel gas	Electricity, some marketable fuels	Char ash metals recycle or landfill	Moderate may need refining at additional expense	All organics low moisture
Anaerobic Digestion	Fuel Gas (CH_4 and CO_2)	Heat, Power, Fuels, Chemicals, Soil Amendment	Inorganics, metals, glass, undegraded biomass	Moderate to High	Biodegradable Components
Fermentation	Ethanol	Ethanol, Chemicals, Heat, Soil Amendment	Inorganics, metals, glass, undegraded biomass	Moderate to High	Biodegradable Components
Aerobic Digestion (Composting)	Soil Amendment	–	Inorganics, metals, glass, undegraded biomass	Low to Moderate	Biodegradable Components

The impact of the use of conversion technologies on recycling markets is an important issue. With the development of conversion technologies that can process a broader range of waste than current recycling practices, it is possible that much of the difficult-to-recycle materials may find a market in conversion. Correspondingly, wider use of conversion technologies would likely result in greater effort in the preprocessing or sorting of waste streams that are currently being sent directly to landfill. These offsetting factors were evaluated as part of a market study being conducted in conjunction with project. Overall, as part of this marketing study, it was concluded that recycling would increase due to greater effort in sorting of the waste. It should also be noted that if conversion technologies are operated in a mode designed to produce petroleum or other chemical-based products such as ethylene, it is possible that these products could be used to reproduce plastics or other materials, creating a new avenue for the generation of recyclable materials.

6.6 Socio-Political

The widespread implementation of conversion technologies for the diversion of waste would likely have a significant impact on waste management as well as society as a whole. From a socio-political standpoint, the areas of impact could include enhanced revenues from landfill diversion, lower environmental impacts, development and processing of previously underutilized resources in new product markets, and the economy. While this study reviews and provides preliminary evaluations in some of these areas, a more comprehensive study of the relationship between these various factors is necessary to better understand the social benefits and liabilities due to adoption of conversion technologies in California. This could include life-cycle analysis of all waste management options, or a more detailed analysis of some of the individual areas, such as the net economic effects on the production and use of organic materials. The focus of this section is primarily to point out issues that need to be considered in this context.

Environmental considerations are one of the most important factors in evaluating conversion technologies. Since there are a number of competing factors in evaluating the environmental impacts, it is important that these issues be addressed using a full life-cycle analysis. For example, the gaseous emissions and liquid and solid residues from conversion technologies should be compared against the emissions/impact from existing practices such as landfilling, or the production of the products such as transportation fuels and other chemicals. This would include comparisons with natural gas and coal-fired power plants and landfill gas emissions.

Conversion technologies will extend the life of currently permitted landfills and reduce the need for further development and siting of landfills. The reduction or elimination of landfill material will eventually reduce the amount of landfill gas emitted into the air as well as other environmental impacts such as leachate incursion to ground water, pestilence, traffic, etc.

The development of conversion technologies could provide an alternative method of the production for various fuels, chemicals and electricity. This would help to reduce the need for out-of-state or foreign resources to meet this demand. This could also provide diversity and more competition in the marketplace for fuels, chemical and energy products.

Economically, the application of conversion technologies would likely have significant impact on the revenues at individual MSW facilities, as well as providing an enterprise for job growth and in various product markets.

Conversion technologies could potentially contribute to a more sustainable future than what would result if the current practice of landfilling large amounts of organic (energetic) materials remains unchanged. This prospect should be evaluated in the context of the feasibility of other practices such as material recycling and waste reduction at the source level, to determine the equilibrium between production and disposal of producer goods, and assess the degree to which achieving this equilibrium would lead to greater sustainability in the future.

6.7 Overall Conclusions

On the basis of the information evaluated in this report, alternative thermochemical and biochemical conversion technologies represent technically viable options for the conversion of post recycled MSW. Thermochemical and biochemical conversion technologies possess unique characteristics which have varying potentials to reduce landfill amounts. In some cases, combinations of these technologies are likely to be used in addressing post-recycled MSW.

Despite expressed interest by the state in reducing waste disposal, current policies have not achieved this result. The population of California continues to grow as does the per-capita waste disposal rate. If these trends continue, landfill material flow will continue to increase as well. Adoption of conversion technologies in California will depend in large part on public acceptance. Credible technical and environmental information, public education, and equitable and sound policies will be critical to future development efforts aimed at reducing landfill disposal. Disparities in diversion credit allowances among conversion technologies, for example, may unnecessarily constrain industry innovation and limit future state options for waste management and resource utilization. Detailed open and objective life cycle and other assessments coupled with rigorous testing and analysis will be important in advancing environmentally preferred solid waste management strategies in the State.

Thermochemical conversion technologies, such as gasification and pyrolysis, can treat nearly all of the organic fraction of MSW and can, in general, treat a more heterogeneous feedstock, including high energy content plastics. Pyrolysis and gasification applications for MSW have expanded considerably in the past 5 years, especially in Japan that has limited domestic resources and limited landfill space. Over 50 commercially active gasification and pyrolysis facilities were identified with a total capacity representing approximately 6% of the current landfill stream in California. Of the two methods, gasification is more technologically complex but offers the capability of producing a broader array of products without additional upgrading.

The use of biochemical technologies for processing fractions of the MSW stream has also increased significantly over the past 5 years. This includes processes such as anaerobic digestion and fermentation. Biochemical technologies are more limited in their application since they can only process biodegradable feedstocks. Most of the growth in biochemical technologies has been in Europe due to a combination of high tipping fees, restrictions on landfilling untreated waste, and high prices for renewable energy products. Currently, the European capacity of anaerobic digestion for MSW components represents approximately 7% of the current landfill stream in California. Biochemical technologies could also be used in combination with alternative thermochemical or other processes to provide broader reduction of landfilled material.

Feedstock selection and processing will depend on the specific requirements of each conversion technology being used as well as other local economic considerations. Current policies in California would require that conversion processes use up-front sorting processes to remove inorganic metals, and other potentially recyclable materials such as paper and some plastics. Additional sorting would likely be required for biochemical process to provide an input stream that is composed of essentially biodegradeable products. This would exclude the majority of the plastic and textiles. For thermochemical processes, materials that would contribute to toxic or other air pollutants could also be removed, if necessary. This could include feedstocks with high Cl content such as PVC or other feedstocks with significant quantities of volatile metals such as batteries. Air pollution controls will be needed in addition to the preliminary sorting so that a complete clean sort would not likely be required.

Existing data and facilities in locations worldwide indicate that conversion technologies can operate within constraints established by regulatory requirements. There has also been considerable technological progress in emissions controls over the past decade that can be directly applied to conversion technologies. These factors indicate that it is very likely that conversion technologies with the most advanced environmental controls would be able to meet regulatory requirements in California. The environmental risk of conversion technology facilities appears to be comparable with current landfill practices and other common industrial practices provided the facilities are properly designed and operated. However, the impacts of specific facilities will need to be evaluated on a “case-by case” basis as part of the local permitting process.

The viability of any single facility will depend on a number of factors including social and economic considerations,, and feedstock requirements and availability. While facilities are becoming operational throughout the world, the technological and economic risk will be facility-dependent. Given the heterogeneous nature of MSW feedstocks and relatively low tipping fees and product prices, some risk remains with the use of conversion technologies. A number of facilities were identified that were unsuccessful for a variety of technical or economic reasons. Considering the potentially large market size and the rapid progress towards commercialization, however, conversion technologies appear to be well on their way to technological maturity in terms of efficiency and reliability.

Conclusions regarding the technologies investigated in this report are summarized in Table 6-4.

Table 6-4. Summary of the General Processes Considered in Report

Conversion Technology	Landfill Reduction Potential	Environmental Impact	Status of Technology	Socio- Economic	Products	Residual
Complete gasification	All organics low moisture	Low within regulatory constraints	Commercial scales are operational	Needs public education of benefit/value	Synthesis or fuel gases	Ash metals
Hydro-gasification with steam pyrolysis	All organics wet or dry	Low within regulatory constraints	Precommercial	May provide sustainable solutions for MSW	Synthesis or fuels gases	Ash metals
Pyrolysis	All organics high moisture	Moderate within regulatory constraints	Commercial scales are operational	Needs public education of benefit/value	Fuel gases, pyrolytic oils and char	Char ash metals
Biochemical conversion technologies	Portion (50%) of biomass only	Low GHG CH_4 -	Precommercial and pilot scales are deployed Commercial in Europe	Needs public education of limitations and benefits	Biogas, CO_2 ethanol, and some process heat	Significant Residuals that would go to landfill or to beneficial use for properly separated feedstock

7 Recommendations for Further Effort

California and local jurisdictions will be required to manage an ever increasing amount of solid waste as per capita disposal amounts and population both continue to increase. Whether or not significant waste source reduction is implemented in California, very large waste streams are anticipated for at least the next 40 years. It is inefficient and burdensome to future generations to continue to landfill huge resources. New uses and markets for the material currently landfilled (the post recycled waste stream) should be developed.

Some jurisdictions in California that are currently investigating alternatives to standard landfill practices are meeting public resistance. Resistance is strongest to thermochemical processes with perhaps less resistance offered against biochemical processes. This is unfortunate because the perception seems to be based on the poor reputation earned by the solid waste combustion industry in the 1970s. The current state of the art is much improved and the surviving solid waste combustion facilities are emitting extremely low criteria and hazardous pollutants. The emerging thermochemical conversion systems addressed in this report are expected to meet existing environmental regulations and could have improved performance compared to modern solid waste combustion. New conversion technologies should not be dismissed because of misperception based on old facilities and technologies.

The potential for significant reduction in landfill disposal and use or conversion of materials currently being disposed is possible with an integrated approach that reduces waste production and increases new use of waste material and waste conversion will have an important role.

The following are recommendations related to the area of conversion technologies.

- It is suggested that the definition provided in AB 2770 for gasification be revised to provide a more scientifically correct description of the gasification process, if needed. An improved definition is contained in this report as follows:

  > "Gasification refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H_2, methane, and lighter hydrocarbons in association with CO_2 and N_2 depending on the process used."

- A more formal evaluation should be conducted of conversion technology vendors interested in marketing in California. This evaluation should include more specific information than can be obtained in a scoping study such as the present work. This information should include economic cost estimates, emissions data from third-party sources, and more specific detail on commercial status, including possible site visits for a limited number of already commercialized technologies. This evaluation should be conducted by a neutral, independent, third party.

- The State should investigate conversion technologies including, perhaps, sponsorship of pilot scale demonstration facilities within California which can be rigorously analyzed and operated with full public participation in order to develop verifiable and trusted operational data. A steering committee of stakeholders should be included at the outset.

- Additional data should be collected on emissions from thermochemical and biochemical conversion technologies, including commercial facilities where they exist and future pilot facilities as recommended above. These emissions studies should be conducted by an independent third party and could include facilities at locations throughout the world, or most importantly in California as facilities become available. These emissions studies should include measurement of metals, dioxins and furans, other hazardous compounds, and fugitive gas and particulate matter emissions, in addition to criteria pollutants. The emissions results should be normalized to a standard use indicator such as volume or mass of material processed so that the values can be compared with other processes. These characterizations are typical of the type performed in life cycle assessment. Measurement of the composition of synthesis gas and other products prior to any combustion may also be useful in evaluating the system as a whole.

- Improve the characterization of MSW. To predict the behavior of conversion systems and estimate type and quantity of emissions, detailed chemical composition and physical property data for feedstocks are necessary. Much information exists in the literature, but a review should be done to determine whether sufficient data exist for California waste streams. Where gaps are identified in the data, samples of California waste streams should be analyzed to fill these information gaps. The type of characterization by component and by gross sample includes:

    - Proximate, ultimate, and other elemental analysis including ash, metals, and toxic cogeners
    - Higher heating values (HHV)
    - Structural carbohydrate analyses (cellulose/hemicellulose/lignin) for cellulosic components
    - Protein/carbohydrate/fats for typical food and other wastes

  Recommendations could be made on the basis of these results as to which components should be pre-sorted from MSW being used for conversion.

- Create co-funding methods to encourage the commercial development suitable for MSW conversion facilities. These could be co-located with existing landfills, material recovery facilities (MRFs), and other waste handling operations for maximum effectiveness in promoting reduction of mass flows into present landfills.

- Investigate issues and feasibilities of “complete stream recycling parks” (also called “ecoparks”) where current waste material enters the facility, is sorted and sent to processes that make best use of the material. Feasibility of biorefineries handling solid waste, possible mixed with other biomass streams, should also be investigated. Ideally, there would be no unvalued residues left for disposal.

Glossary of Terms

This glossary contains general definitions of some terms that appear in the report. Additional descriptions can be found elsewhere such as http://www.eere.energy.gov/biomass/gasification.html and the McGraw-Hill Encyclopedia of Science and Technology Online (http://www.accessscience.com/).

- *Carbonization*:

A low temperature and high residence time pyrolytic process designed to produce the maximum quantity of char. Typically used to make char coal from wood.

- *Combustion:*

A rapid conversion of chemical energy into thermal energy. The reaction is exothermic. Organic matter is oxidized with sufficient air (or oxygen) for reactions to go to completion. The carbon and hydrogen are oxidized to carbon dioxide and water, respectively.

- *Digestion*:

Either in the presence of oxygen (aerobic) or in an oxygen-depleted atmosphere (anaerobic), digestion is the process in which microbes digest biogenic carbonaceous materials and emit any number of energetic, inert gases and liquids.

- *Elutriation:*

The separation of finer lighter particles from coarser heavier particles in a mixture by means of a usually slow upward stream of fluid so that the lighter particles are carried upward*.*

- *Entrain:*

To carry (suspended particles, for example) along in a current.

- *Extended Producer Responsibility (EPR)*

EPR as it relates to solid waste management refers to responsibility placed on waste producers for disposal or mitigation of their own waste. 'Producer pays' or 'take-back' laws are examples of implementing EPR.

- *Fermentation:*

The use of microorganisms such as yeast, bacteria, and fungi to convert substrates such as sugar into products. In the absence of oxygen, these products can include ethanol, methane, and carbon dioxide plus some increase in cell mass. When oxygen is present, the increase in cell mass is generally much greater with water and carbon dioxide usually the primary products.

- *Fischer-Tropsch:*

Fischer-Tropsch synthesis is a process for producing mainly straight-chain paraffinic hydrocarbons from a synthesis gas having the correct mixture of CO and H_2. Catalysts are usually employed. Typical operating conditions for FT synthesis are temperatures of 390-660 °F and pressures of 15-40 atmospheres depending on the desired products. The product range includes the light hydrocarbons methane (CH_4) and ethane (C_2), LPG (C_3-C_4), gasoline (C_5-C_{12}), diesel (C_{13}-C_{22}), and waxes (>C_{23}). The distribution of the products depends on the catalyst and the process conditions (temperature, pressure, and residence time). The synthesis gas should have low tar and particulate matter content to avoid progressive contamination of the catalysts. Biomass derived synthesis gas for FT liquid production is pre-commercial. However, it may be more easily commercialized than coal since it has smaller quantities of contaminants to remove in the synthesis gas cleaning process.

- *Gasification:*

Production of energetic gases from solid or liquid organic feedstocks usually by partial oxidation. Primary energetic gases produced are hydrogen, carbon monoxide, and methane, along with an inorganic ash residue.

- *Hydrogasification:*

Gasification using hydrogen gas to react with the carbon in organic materials to produce a methane rich gas effluent, and provide heat for the process. Any pyrolytic products present are usually converted into methane. Steam pyrolysis is often used as a precursor process that can enhance the hydrogen reaction kinetics, despite the presence of water in the feed. Since oxygen is not intentionally introduced, carbon oxides are reduced and methane increased as the hydrogen pressure is increased. Toxic hydrocarbons, like furans and dioxins, are chemically reduced by hydrogasification to less hazardous chemical compounds.

- *Hydrolysis:*

A chemical or biological process in which water is added to other molecules (the conditions are wide ranging and many molecules can be hydrolyzed). Hydrolysis is a pre-treatment or preliminary step in fermentation processes that ultimately yield biogas or ethanol. For cellulose and hemicellulose, a variety of hydrolysis methods can be used to break down the long chain polymer into simple glucose molecules, Efficiencies of hydrolysis vary among methods and feedstocks.

- *IGCC:*

Integrated gasifier combined cycles (IGCC), are combined cycle systems that incorporate a gasifier for the purposes of converting the solid fuel to a fuel gas for combustion in a gas turbine using the Brayton cycle. Combined cycle (CC) power systems can extract more useful energy from a given amount of input energy or fuel by utilizing two power cycles in sequence: 1) a gas turbine Brayton cycle and 2) a steam Rankine cycle utilizing heat rejected in the gas turbine exhaust. In such systems, the steam boiler is conventionally referred to as a heat recovery steam generator (HRSG). Gas turbines require a clean, particle free exhaust gas for expansion through the turbine. Using the effluent gases from gasified biomass or coal as a turbine fuel requires cleanup before introduction to the combustion chamber of the turbine, similar to those present in commercially cleaned natural gas. Gasification of coal for IGCC is being done in over 20 facilities worldwide.

- *Incineration:*

A generic term in the industry that connotes any process that combusts waste.

- *Mass Burn Incineration:*

Combustion of solid wastes that have had no sorting or pre-treatment applied. The whole solid waste 'mass' if used as feedstock. Heat and power may or may not be recovered.

- *Organic*:

Material containing carbon and hydrogen. Organic material in MSW includes the biomass components of the waste stream as well as hydrocarbons usually derived from fossil sources (e.g., most plastics, polymers, the majority of waste tire components, and petroleum residues).

- *Pyrolysis:*

A thermal degradation of carbonaceous material in an oxygen-free reactor. Pyrolytic oils, fuel gas, chars and ash are produced in quantities that are highly dependent on temperature, residence time and the amount of heat applied.

- *Rankine cycle:*

The Rankine vapor power cycle is the most widely used thermal cycle for electrical power generation throughout the world. It is commonly called a 'steam cycle' when the working fluid is water. It consists of a boiler where heat is added to liquid phase pressurized working fluid (water) to create a high temperature and pressurized vapor (steam if the working fluid is water). The high-pressure steam is expanded through a turbine, which turns a generator creating electrical power. The low-pressure steam coming out of the turbine is condensed to liquid by cooling after which the pressure of the relatively low temperature liquid is raised by a boiler feed pump or pumps to repeat the cycle. Rankine cycle efficiencies depend on plant size, fuel, and design and typically vary from about 10% for very small (< 1 MW_e) solid-fueled systems to greater than 40% for large (>500 MW_e) supercritical units. Typical solid-fueled biomass and waste fired power plants (~10-100 MW_e) have net efficiencies of about 17-25%.

- *Starved air incineration:*

This process is usually two fold. In the first stage, the reactor is fed with sub-stoichiometric levels of oxygen, which creates a reducing environment, driving the organic components into the gas phase and leaving the inorganic material as ash residue. The next stage that follows thermally oxidizes the organic gases by mixing with excess oxygen.

- *Steam reforming:*

An endothermic chemical conversion process used to make hydrogen and carbon monoxide from superheat steam and hydrocarbon gases, such as methane using a nickel based catalyst.

- *Steam pyrolysis:*

A thermally driven decomposition of organic material in a high pressure superheat steam reactor. The steam produces more gas products and less pyrolytic oil than dry pyrolysis. The pyrolytic char formed is highly porous and is often used to make activated carbon from waste biomass. The activation of the char, enhances the reactivity of the gasification process, especially when using hydrogen.

- *Stoichiometry:*

Generally the molar or mass relationships among reactants and products of a chemical reaction. In any combustion reaction, for example, there is a specific molar or mass ratio of oxygen or air (contains 21% oxygen by volume) to fuel that is required for complete combustion to occur (fuel fully oxidized to carbon dioxide and water). This ratio is called the stoichiometric ratio or the stoichiometric air-fuel ratio. The inverse ratio is referred to as the stoichiometric fuel-air ratio. If excess oxygen or air is supplied, the combustion occurs under fuel-lean conditions. If insufficient oxygen or air is supplied, the combustion is fuel-rich. The ratio of the stoichiometric air-fuel ratio to the actual air-fuel ratio is called the equivalence ratio (ϕ), so that fuel-lean conditions occur at equivalence ratios less than 1, and fuel-rich conditions occur at equivalence ratios greater than 1. An equivalence ratio equal to 1 specifies the stoichiometric air-fuel ratio. The inverse of the equivalence ratio is the air- or lambda-factor (λ). Combustion conditions are commonly described by the equivalence ratio, while gasification conditions (extremely fuel rich) are commonly described by the air-factor.

- *Synthesis gas:*

A mixture of carbon dioxide, carbon monoxide and hydrogen gas formed via gasification for the express purpose of synthesizing products.

- *Thermal oxidation:*

A high temperature oxidative process that uses excess oxygen to convert gaseous organic matter into carbon dioxide and water vapor.

- *Volatile Solids:*

Volatile solids (VS) amount is determined by an analytical method called "loss on ignition." It is the amount of matter that is volatilized and burned from a sample exposed to air at 550 ºC for 2 hours. The organic (carbon containing matter) is lost and the remaining matter is the mineral or ash component of the original sample. VS is usually reported as percent of total solids (TS). TS are the sum of the VS and ash components. TS are usually reported as percent of total sample weight (wet basis). The moisture content of the sample (in percent) is simply 100 – TS.

List of Appendices

Abbreviations and Acronyms

AB	California assembly bill
ACTP	alternative conversion technology plants
AD	anaerobic digestion
ADC	alternative daily cover
ASR	automobile shredder residue
atm	atmospheres
BFB	bubbling fluidized bed
BGL	British Gas- Lurgi
BIGCC	Biomass integrated gasifier combined cycle
BMP	biochemical methane potential
Btu	British Thermal Unit
CC	Combined Cycle
CEC	California Energy Commission
C&D	construction and demolition
C/N	carbon/nitrogen ratio
ca	capita
CADDET	Centre for Analysis and Dissemination of Demonstrated Energy Technologies
CEC	California Energy Commission
CFB	circulating fluidized bed
CIWMB	California Integrated Waste Management Board
CV	calorific value
d	day
DME	dimethyl ether
DOE	Department of Energy
DPPP	Dairy Power Production Program
EC	The European Council
EJ	10^{18} joules (exajoule)
EPR	Extended Producer Responsibility
ETS	enhanced transfer stations
FT	Fischer-Tropsch
GAIA	Global Anti-Incinerator Alliance
GWh	gigawatt-hour (10^9 watt-hours)
h	hour
HHV	higher heating value
HRSG	heat recovery steam generator
HS	high solids

IEA	International Energy Agency
IGCC	integrated gasifier combined cycle
kg	kilogram
kW	kilowatt
kWh	kilowatt - hour
LFG	landfill gas
LS	low solids
MACT	maximum available control technology
MBT	mechanical biological treatment
MJ	10^6 joules (megajoule)
MMBtu	million Btu
MRF	material recovery facility
MS	multi-stage
MSW	Municipal Solid Waste
Mt	million short tons
MW	megawatt
MW_e	megawatt of electricity
MWh	megawatt-hour
MW_{th}	megawatt of heat
NETL	National Energy Technology Laboratory
Nm^3	normal cubic meter
NREL	National Renewable Energy Laboratory
OCC	old corrugated containers
ofMSW	organic fraction of MSW
ONP	old newspaper
OS	one-stage
PCDD/F	polychlorinated dibenzo-p-dioxins and dibenzofurans
Quad	10^{15} Btu (Q)
RDD&D	research, development, demonstration and deployment
RDF	refuse derived fuel
REOI	request for expression of interest
RFI	request for information
RFP	request for proposal
Short ton	US customary ton (2000 lb)
TEQ	Toxic equivalent
TOC	Total organic carbon
ton	short ton (2000 lb)
tonne	metric ton (1000 kg = 1 Mg)
TWh	terawatt-hour (10^{12} watt-hours)

VCM	vinyl chloride monomer
wb	wet basis
WWTP	wastewater treatment plan
y	year

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